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Removal of Persistant Contaminants from Municipal Effluents by Reverse Osmosis

Research Report No. 85

esearch Program for the Abatement of Municipal Pollution under Provisions of the Canada-Ontario Agreement on Great Lakes Water Quality

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REMOVAL OF PERSISTENT CONTAMINANTS FROM MUNICIPAL EFFLUENTS BY REVERSE OSMOSIS

by

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Wastewater Technology Centre
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ENVIRONMENT CANADA

RESEARCH PROGRAM FOR THE ABATEMENT
OF MUNICIPAL POLLUTION UNDER THE
PROVISIONS OF THE CANADA-ONTARIO
AGREEMENT ON GREAT LAKES WATER QUALITY

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ABSTRACT

The effectiveness of the reverse osmosis process in removing specific toxic substances from municipal effluents was studied. The toxic substances considered were: arsenic, selenium, cyanide (simple and complex salts), nitrilotriacetic acids (NTA), phenols, aldrin, DDT, chlordane, endrin, melathion, and parathion. Experiments were conducted in the laboratory and in a specially equipped mobile pilot plant. Data on removal efficiencies are presented along with reverse osmosis (RO) system permeation rates and variations in those rates with time. Membrane fouling problems and cleaning methods were examined and are reported on.

Chlorinated hydrocarbon and organic phosphate pesticides are almost completely removed by RO while the heavy metal removal rate was consistently greater than 95%. The removal rates for other substances examined such as: complex cyanide, NTA, selenium, arsenic and phenols, varied between 43% and 90%.

RÉSUMÉ

Le procédé de l'osmose inverse (O.I.) a été expérimenté en laboratoire et dans une installation pilote mobile spécialement équipée, afin d'en vérifier l'effet sur l'élimination des toxiques suivants des effluents urbains: arsenic, sélénium, cyanures (simples et complexes), acides nitrilotriacétique (ANT), phénols, aldrine, DDT, chlordane, endrine, malathion et parathion. Le présent rapport contient les données sur l'efficacité d'épuration, en même temps que sur le taux de filtration de l'O.I. et la variation de ce dernier en fonction du temps. Les problèmes de colmatage et les méthodes de nettoyage ont été examiné et y sont également commentés.

Les pesticides organochlorés et organophosphorés sont presques entièrement retirés par l'O.I., tandis que les métaux lourds le sont à 95 p. 100 et plus. Les autres substances comme les cyanures complexes, l'ANT, le sélénium, l'arsenic et les phénols sont supprimées 43 à 90 p. 100.

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CONCLUSIONS

Heavy metals can be effectively separated from water and secondary municipal effluents by reverse osmosis. Rejections for all metals examined were above 95% and were generally uniform over a nine-month period.

Various constituents of the secondary effluent were rejected to different extents. Removals were generally higher than the salt rejection ability of the membranes operating under similar conditions with standard NaCl solutions.

The removals of toxic substances from wastewater varied with their chemical nature. Complex cyanide and NTA were almost completely removed by both low (70%) and high (90%) sodium chloride rejection membranes. Sodium cyanide rejection was 43%. Selenium and arsenic removals exceeded the NaCl rejection abilities of the membranes.

Phenols were poorly rejected by cellulose acetate membranes, but were about 60% to 75% rejected by aromatic polyamide membranes.

Pesticides and organic phosphates could be almost completely removed from the water. However, the separation was largely due to the sorption of the organics on the membrane surface.

1 INTRODUCTION

Reverse osmosis is a separation/purification technique that offers some potential for the treatment of waste treatment plant effluents. To assess the suitability of RO as a tertiary, secondary and even primary municipal renovation technique, a two-stage research program was undertaken. The first part of the program, completed in August, 1974, focused on the ability of RO to remove nutrients and residual chemical additives from secondary effluents (Johnston and Lim, 1977). The suitability of this technique for removing specific constituents (such as total organic carbon [TOC], chemical oxygen demand [COD], total dissolved solids [TDS], suspended solids [SS], etc.) from the effluent was also evaluated in some detail. Generally, the removal efficiency of the various substances was accomplished with a high degree of efficiency, independent of contaminant concentration and effluent quality.

The second part of this study, as presented herein, examines the ability of RO to remove specific toxic substances from municipal effluents. These substances are heavy metals, pesticides and a variety of other chemicals. Both laboratory and pilot scale units were employed in this investigation.

In many industrial situations, the RO process has proven excellent for concentrating or reclaiming specific chemicals and materials. These substances are usually in relatively high concentrations and the waste streams treated often contain only a few contaminants (Johnston and Lim, 1974). Concentration for disposal or reuse is, therefore, greatly simplified. However, limited attention has been paid to the use of RO as a municipal wastewater treatment technique where low concentrations of heavy metals and toxic chemicals are encountered in both the dissolved and suspended form. Higher concentrations of non-toxic organic, inorganic, dissolved or suspended solids would probably exert a strong influence on the efficiency of the RO process. The extent of this influence and the removal efficiencies of RO for specific toxic chemicals under such field conditions had not been properly assessed prior to this program.

2 OBJECTIVES

The overall objective of this program was to assess the effectiveness of reverse osmosis in the treatment of municipal waste treatment plant effluents. Emphasis in this second part of a two-phase program was placed on the ability of RO to remove heavy metals and specific organic and inorganic toxic substances from prepared solutions and from municipal waste treatment plant effluents.

Preliminary evaluations of the removal efficiencies for specific constituents were made on artificial waste solutions in laboratory test cells. Based on the knowledge gained, optimum operation of the pilot plant, which was designed to evaluate the long term effectiveness of the treatment technique under field conditions, was achieved.

3 EXPERIMENTAL SECTION

Both laboratory and pilot plant test equipment utilized during this study employed cellulose acetate reverse osmosis membranes. Membranes for the laboratory test cells were prepared in the fabrication facilities of the Canada Centre for Inland Waters (CCIW) as outlined by Johnston and Lim, 1977. The pilot plant unit was a modification of a commercial unit from Westinghouse Electric Corporation, which employed tubular membranes. All laboratory and pilot plant equipment, as well as the relevant operating techniques, were outlined in detail by Johnston and Lim, 1977.

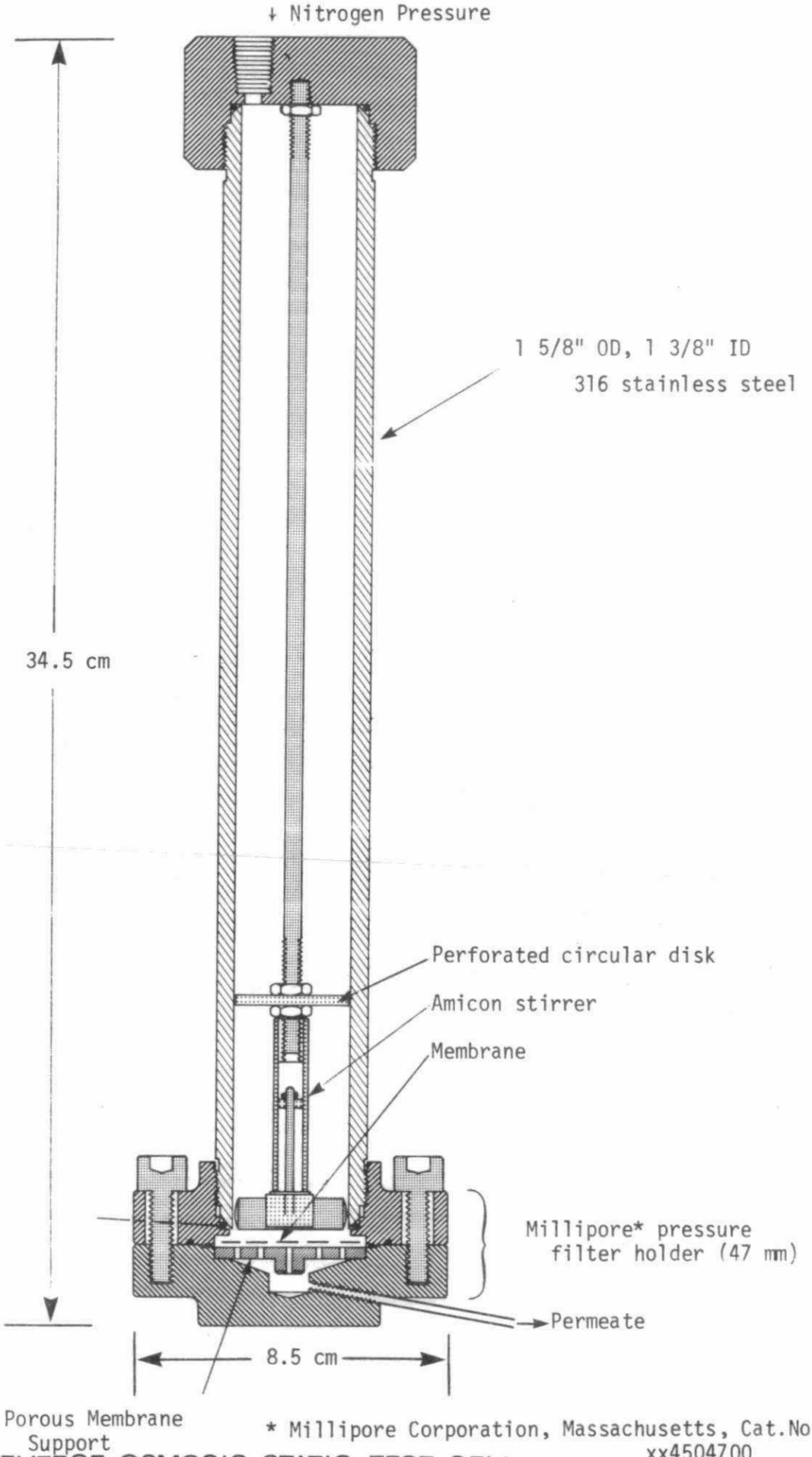
3.1 Laboratory Study

The static test cell, as shown in Figure 1, was employed in all laboratory studies. Cellulose acetate membranes capable of rejecting 70% and 90% solute from a standard 3500 mg/L NaCl solution were prepared at CCIW and routinely employed during this study. The effective membrane area in the cell was 13.3 cm^2 (5.2 in^2). Pressure in the static test cell was supplied by a cylinder of compressed nitrogen gas at a pressure of 1724 kPa (250 psi). An externally controlled magnetic stirrer provided the turbulence that was necessary to ensure consistent and efficient operation in the cell.

Eighteen metal chloride salts in pure water were individually examined to determine their rejection levels by RO. Most of these metal salts were divalent, although three trivalent and one monovalent salt were also examined. Tests were conducted for all metals at 10 mg/L (as metal) solutions. In addition, a limited number of metals were examined at concentrations ranging from 1 to 1000 mg/L to determine the concentration effect, if any, on their removal efficiencies.

3.1.1 Removal of toxic chemicals

A series of toxic chemicals, both organic and inorganic, were selected on the basis of their observed lethal concentrations (Jordening and Allwood, 1973) and their potential threats to Canadian water systems. The toxic chemicals selected were arsenic, selenium, cyanide (simple and complex salts), nitrilotriacetic acid (NTA), phenols, aldrin, dichlorodiphenyltrichloroethane (DDT), chlordane, endrin, malathion, and parathion. The



* Millipore Corporation, Massachusetts, Cat.No. xx4504700

FIG.1 **REVERSE OSMOSIS STATIC TEST CELL**

pesticides were generally only sparingly soluble. Thus, the concentrations employed varied, depending on their solubilities as well as their lethal concentrations.

3.2 Pilot Plant Study

3.2.1 Equipment

The reverse osmosis pilot plant was installed in a 5.5 x 2.4 m (18 x 8 ft) enclosed trailer and was on-site at the Wastewater Technology Centre (WTC), Burlington. Influent to the RO pilot plant was chlorine free secondary effluent from an extended aeration pilot plant. A simplified flow diagram of the RO pilot plant is presented in Figure 2 with a more detailed schematic presented in Figure 3. The RO system, which consisted of five $NaCl_{90}$ modules and three $NaCl_{75}$ modules, initially produced 4.54 m^3/d (1000 Igpd) of treated water.

3.2.2 Operation

The pilot plant commenced processing secondary effluent on April 3, 1974, and terminated on December 24, 1974, a total of nearly nine months of continuous operation. From April 3 to October 10 all eight modules were in continuous operation. In early October, a membrane failure was discovered in one of the $NaCl_{75}$ modules and the salt rejection ability of the other two $NaCl_{75}$ modules had decreased to less than 50%. As a consequence, all the $NaCl_{75}$ modules were isolated. However, the system continued to operate with the five $NaCl_{90}$ modules from October 10 to December 24.

The first part of this program dealt with nutrient removals and was conducted during the first four months of the pilot plant operation (Johnston and Lim, 1977). Composite samples were collected also for the heavy metal study during this period. Operating conditions and procedures for the heavy metal phase of this study were, therefore, similar to those in the first part of the program. Briefly, the pilot plant system was operated for 22 hours a day at 2068 kPa (300 psi), 27°C (80°F) and 0.3 L/s (4 Igpm) feed flow rate. At the end of each run, the system was flushed for 15 to 30 minutes with tap water at a higher flow rate under reduced pressure. Complete

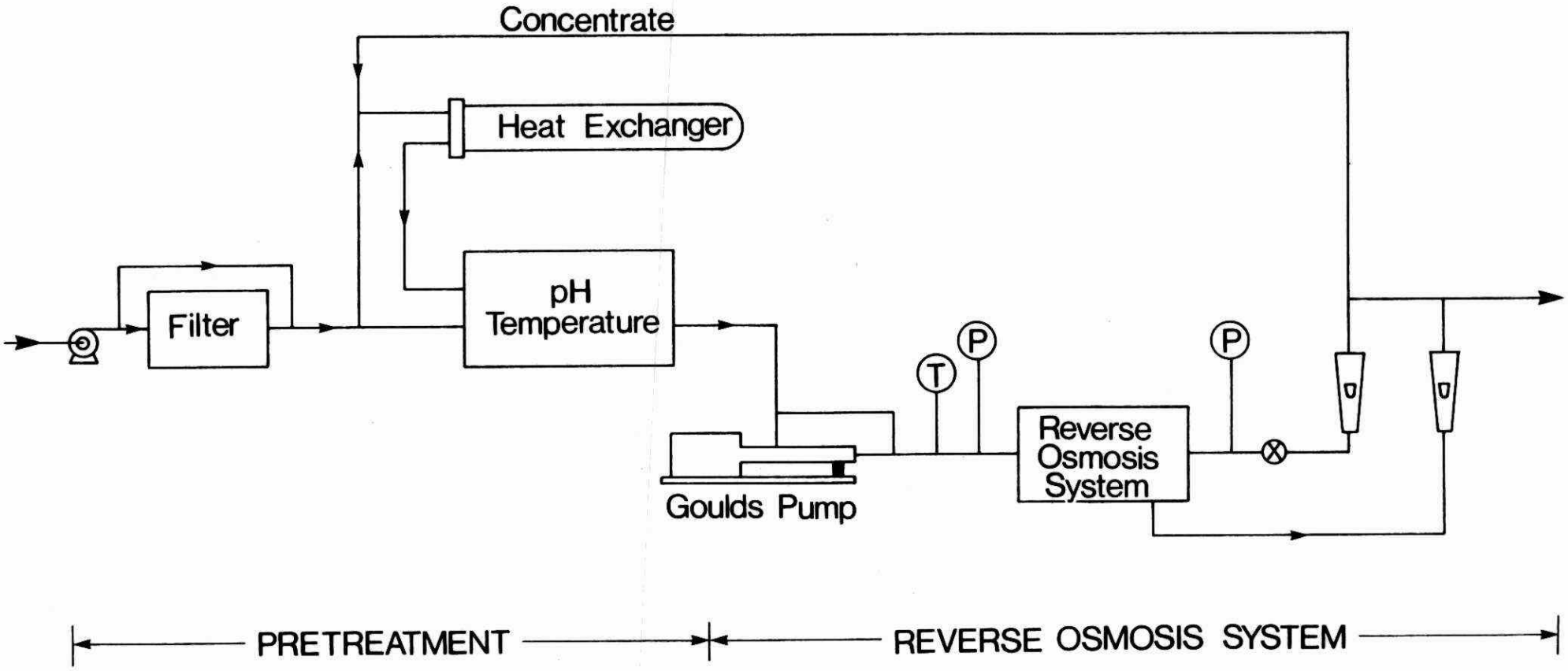


FIG.2 SIMPLIFIED FLOW DIAGRAM OF THE REVERSE OSMOSIS PILOT PLANT

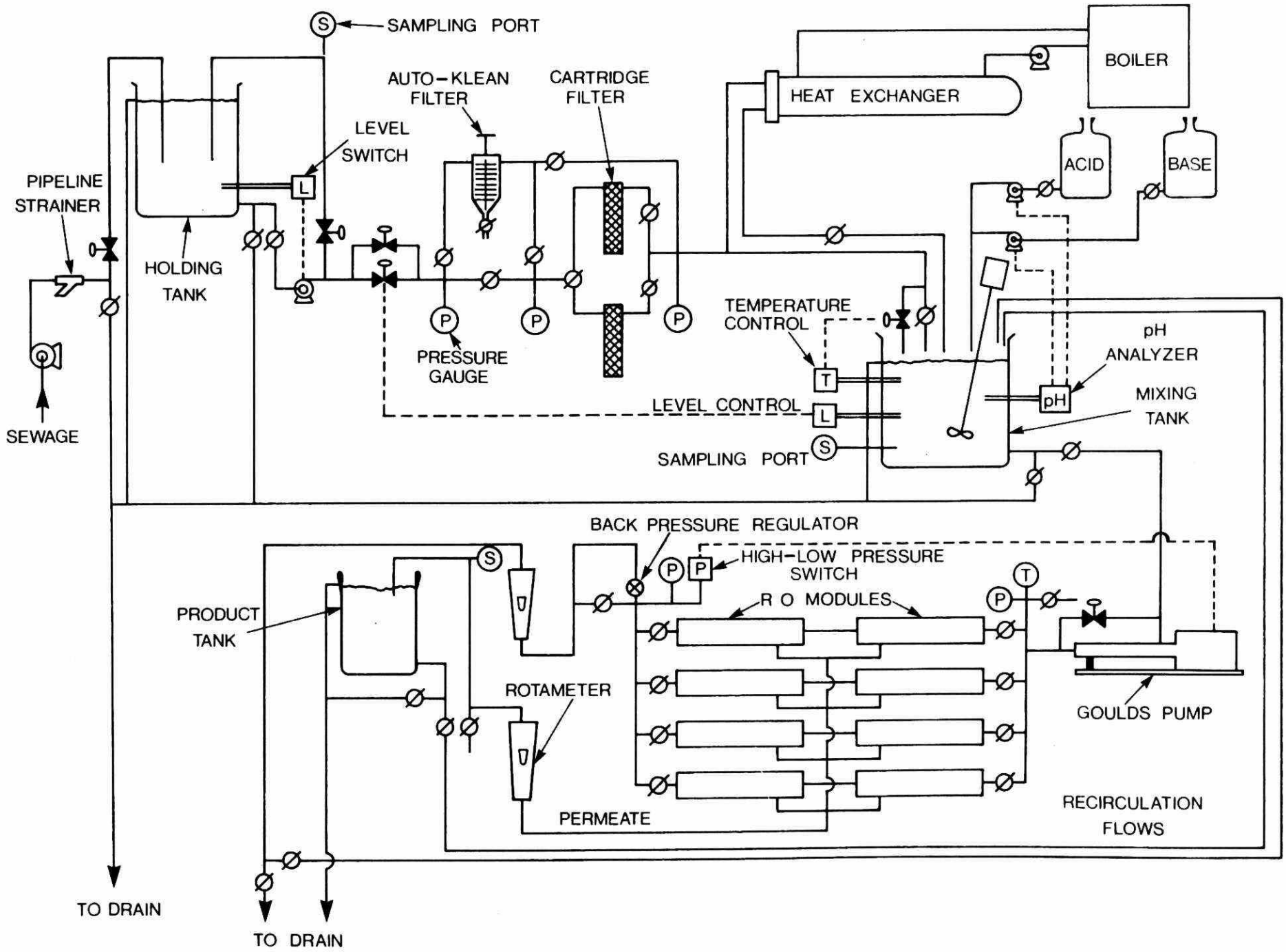


FIG.3 DETAILED SCHEMATIC DIAGRAM OF THE REVERSE OSMOSIS PILOT PLANT

shut-down for one hour followed. Salt permeation tests and membrane cleanings were conducted at regular intervals to monitor and maintain the membrane performance.

These operating conditions and procedures were slightly modified after October 10, 1974, in accordance with the conclusions drawn from this study. The feed flow rate was increased to 0.6 L/s (8 Igpm) to maximize the turbulence in the modules. Partial recycling of the concentrate was implemented to utilize some of the heat of friction generated in the system. This helped to heat up the incoming effluent. Thus, heating was required only on initial start-up of the unit. Once operating conditions were reached, heating was no longer required and slight cooling was sufficient to maintain constant feed temperature.

Composite samples were routinely collected with two ISCO* model 1391 automatic water samplers. Samples for metal analyses were acidified for preservation. The same series of chemical constituents (except nutrients and BOD_5) examined in the first part of the program was determined (Johnston and Lim, 1977). Toxic chemicals were not monitored in the pilot plant study.

3.2.3 Spiked heavy metals study

The extended aeration pilot plant at the Wastewater Technology Centre received its raw sewage (mainly domestic) from the Burlington Skyway Sewage Treatment Plant (BSTP) and the heavy metal concentrations in the effluent were found to be low. Experiments to determine the effectiveness of RO in removing heavy metals were, therefore, conducted with spiked effluents. In this manner, detectable metal concentrations were maintained in the effluent. Twelve metal chloride salts were used to spike the secondary effluent to concentrations of 1, 5 and 10 mg/L of metal. Since the spiking was batchwise, the system was operated in a complete recycle mode, i.e., both permeate and concentrate were recirculated back into the feed system. Continuous spiking of the secondary sewage was also conducted in a different series of experiments. A stock solution of heavy metals was metered into a mixing tank where the metal solution mixed with the returning concentrate and the effluent. A controlled amount of concentrate $(x(1-a)/a)$ was continuously

---

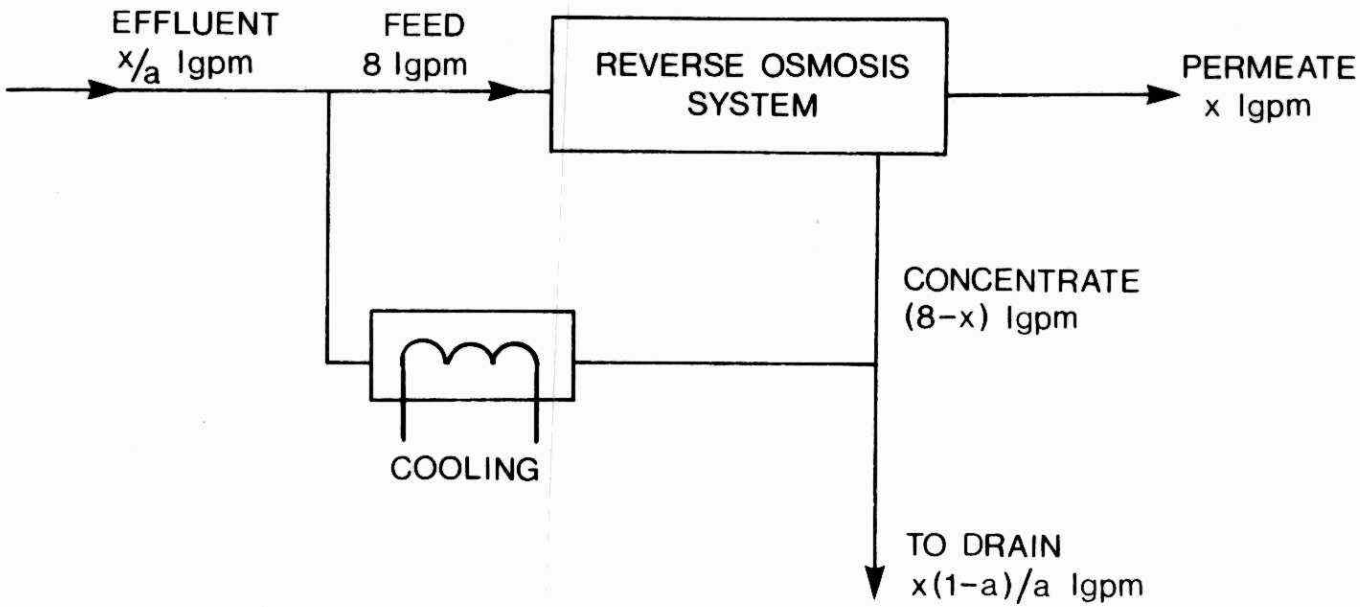
* Instrumentation Specialties Company, Lincoln, Nebraska, U.S.A.

wasted as shown in the Mass Balance Diagram, Figure 4, so that, at steady state, the desired metal feed concentrations were maintained reasonably constant.

3.3 Sample Analyses

All chemical analyses were performed by the Water Quality Laboratory, Inland Waters Directorate (Ontario Region), Department of Fisheries and Environment Canada at the CCIW according to techniques summarized by Traversy, 1971 or compatible with Standard Methods (APHA et al, 1971). Metal concentrations for all samples from the laboratory experiments were determined immediately so that no preservative (acid) was added to the samples. Pilot plant samples for metal analyses were stored in plastic bottles containing 2 mL/L concentrated nitric acid as a preservative. Total metal concentrations were determined for all the pilot plant feed samples, but only extractable metal concentrations were determined for most of the permeate samples (Traversy, 1971). Since the suspended solids in the permeate were negligible (Johnston and Lim, 1977), the extractable metal concentrations were assumed equal to total metal concentration.

The concentrations of pesticides and organic phosphates were determined by a gas chromatographic method. Pure solutions only were examined in the static cells.



$a = \text{Water Recovery Ratio} = {}^{\text{Permeation Rate}}/_{\text{Effluent Rate}}$

FIG. 4 MASS BALANCE DIAGRAM FOR PILOT PLANT OPERATION

4 RESULTS AND DISCUSSION

4.1 Laboratory

Cellulose acetate membranes capable of rejecting 90% and 70% NaCl under standard test conditions were employed in the static cells for all laboratory studies. Standard NaCl rejection tests, conducted daily before the experiments commenced, showed the uniformity of membrane performance. For example, Table 1 illustrates the variability in membrane performance with time for a $NaCl_{90}$ and $NaCl_{70}$ membranes for 45 days. Membranes with higher salt rejection ability (e.g., $NaCl_{90}$) provided more reliable and consistent performance than did lower salt rejection membranes (e.g., $NaCl_{70}$).

4.1.1 Removal of heavy metals

Reverse osmosis was found to be very effective in rejecting the various heavy metals examined. Results are summarized in Table 2. Metals were rejected to different extents, but in all cases the removal efficiencies for the various metals were higher than for NaCl from a standard salt solution. The membrane, capable of rejecting about 70% NaCl from the standard salt solution, was found to reject more than 80% of each of the metals except Mg^{+2}, which was rejected at 73.5%. Separation efficiencies for Al^{+3}, Cr^{+3}, Fe^{+3} and Sn^{+2} approached 100%. When the $NaCl_{90}$ membrane was employed, the rejection levels were all above 90.0%, with many approaching 100%. Trivalent ions were more readily rejected than ions with lower valency. Also, large ions were preferentially rejected over smaller ions. The selective rejection of these metal ions for a given membrane appeared to be controlled by the thermo-dynamic properties of the solutions, specifically the partial molal-free energies of hydration and the entropies of the ions in solution (Johnston, 1974).

The pH of a 10 mg/L metal solution fell within the operating pH range of 3.5 to 8 for cellulose acetate membranes. Therefore, membranes could be efficiently operated with these solutions over extended periods without causing extensive irreversible hydrolysis of the polymer film. The relatively constant membrane performances, as demonstrated by the low standard deviations in Table 1, indicated essentially no deterioration of the membranes. Since the rate of hydrolysis increases in proportion to the flux across the membrane,

TABLE 1. VARIABILITY OF MEMBRANE PERFORMANCE WITH TIME

Operating Time (Days)	MEMBRANE			
	$NaCl_{90}$		$NaCl_{70}$	
	% Rejection[(a)]	Flux[(b)]	% Rejection	Flux
1	91.6	1.54	68.4	4.17
2	90.7	1.67	68.5	4.10
3	89.9	1.62	67.8	4.03
4	90.8	1.68	68.0	4.02
5	91.2	1.68	68.2	4.08
6	91.4	1.73	68.5	4.10
9	91.6	1.71	68.6	4.08
10	91.3	1.71	68.8	4.05
11	91.0	1.70	68.6	4.04
12	90.6	1.69	67.7	
13	91.4	1.70	68.6	4.04
17	91.0	1.71	66.2	4.14
18	91.0	1.71	66.7	4.06
19	90.9	1.71	66.7	4.14
20	91.4	1.70	67.4	4.11
21	89.7	1.68	67.1	4.08
24	90.9	1.73	67.0	4.06
31	90.4	1.70	66.3	3.91
33	91.0	1.65	67.4	3.95
41	91.1	1.71	65.3	4.08
42	92.4	1.71	67.7	4.02
45	91.9	1.69	65.9	3.98
$\bar{X}$ (c)	91.1	1.69	67.5	4.06
σ (d)	0.602	0.015	1.01	0.915
S_m (e)	0.128	0.003	0.214	0.200

(a) Rejection is for a 3500 mg/L NaCl solution tested at 1724 kPa (250 psi)

$$\% \text{ Rej} = 100 \times \frac{C_s - C_p}{C_s}$$ where C_s = solution concentrate; C_p = permeate concentration.

(b) Flux is grams of permeate per hour per cm^2 of membrane area.

(c) $\bar{X}$ is the mean value, defined as: $\bar{X} = \Sigma x / n$.

(d) σ is the standard deviation, defined as:

$$\sigma = \sqrt{\frac{\Sigma x^2 - \frac{(\Sigma x)^2}{n}}{n-1}}$$

(e) S_m is the standard error of the mean, defined as: $S_m = \frac{\sigma}{\sqrt{n}}$

a higher permeation (lower salt rejection) membrane would be expected to hydrolyse faster than a low permeation membrane. Thus, as Table 1 shows, the $NaCl_{70}$ membrane showed a greater decline in performance than the $NaCl_{90}$ membrane.

TABLE 2. METAL REMOVAL EFFICIENCIES BY REVERSE OSMOSIS

Metal Chloride	pH of 10 mg/L Solution	Percent Metal Removal*	
		$NaCl_{70}$	$NaCl_{90}$
(1) K^{+1}	6.3	88.1	94.0
(2) Ba^{+2}	5.8	88.3	100.0
(3) Be^{+2}	4.3	83.8	97.0
(4) Ca^{+2}	5.9	80.8	94.1
(5) Cd^{+2}	5.5	85.1	98.3
(6) Co^{+2}	5.8	81.9	96.0
(7) Cu^{+2}	5.4	84.1	98.6
(8) Fe^{+2}	5.1	82.0	96.2
(9) Mg^{+2}	6.1	73.5	90.0
(10) Mn^{+2}	5.8	84.2	97.5
(11) Ni^{+2}	5.9	81.8	95.2
(12) Pb^{+2}	5.2	85.5	97.6
(13) Sn^{+2}	4.0	99.3	100.0
(14) Sr^{+2}	5.9	84.1	96.3
(15) Zn^{+2}	5.6	83.4	97.3
(16) Al^{+3}	4.4	97.3	100.0
(17) Cr^{+3}	4.2	99.1	100.0
(18) Fe^{+3}	3.4	100.0	100.0

* 10 mg/L solutions tested at 1724 kPa (250 psi).

Separations noted are for metal removals from a 10 mg/L solution when permeated through the reverse osmosis static test cell.

The effect of metal concentration on percent rejection was examined for a limited number of metal chlorides. As Table 3 indicates, the effect of concentration was not pronounced for the $NaCl_{90}$ membrane

within the experimental concentration range studied. The trivalent metals showed virtually no variation with feed concentration. The divalent metals exhibited a slight reduction in rejection at higher concentrations. Due to the consistent and efficient stirring action in the test cells, surface turbulence was maintained at a very high level so that these observed differences in selectivity are due to the nature of the species (Johnston and Lim, 1977). Only the metals of lower valency showed a slight concentration effect on removal efficiency.

TABLE 3. EFFECT OF CONCENTRATION ON METAL REMOVAL

Metal Chloride	% Metal Removal[(a)]			
	Metal Feed Concentration (mg/L)			
	1	10	100	1000
Al^{+3}	99.0	99.1	99.2	99.1
Cr^{+3}		95.6	97.3	94.8
Fe^{+3}	99.0	99.1	99.4	99.2
Co^{+2}		93.6	87.6	91.4
Cu^{+2}		96.9	96.3	97.1
Mn^{+2}		96.5	90.8	91.1

(a) Under 1724 kPa (250 psi) with a $NaCl_{90}$ membrane.

4.1.2 Removal of toxic chemicals

The ability of RO to remove toxic chemicals varied considerably with different chemicals and with different membrane materials. With different combinations of membranes and chemicals, the separation varied from 0% to 100%. To simplify the presentation of these results, the toxic chemicals have been broken down into three generalized groups: toxic metals and NTA; phenols; and chlorinated hydrocarbon and organic phosphate pesticides.

Table 4 summarizes the results for arsenic, selenium, simple and complex cyanides and NTA. The large molecule chemicals such as the complex cyanides and NTA were almost completely removed and the $NaCl_{70}$ membrane achieved the same separation efficiencies as the $NaCl_{90}$ membrane, but at

double the permeation flux. When cyanide existed as a simple salt of sodium, the rejection decreased drastically and the $NaCl_{90}$ membrane removed 15% more cyanide than did the $NaCl_{70}$ membrane. Higher removal efficiency (≈80%) for NaCN has been reported (Hindin and Bennett, 1969) when cellulose acetate membranes, capable of rejecting about 75% salt from an approximately 1000 mg/L NaCl solution, were employed at 10134 kPa (100 atmospheres) pressure.

TABLE 4. REMOVAL OF TOXIC CHEMICALS BY REVERSE OSMOSIS

Chemicals	Ave. Feed Conc.*		pH of Feed	% Removal		Permeate Flux**	
	$NaCl_{70}$	$NaCl_{90}$		$NaCl_{70}$	$NaCl_{90}$	$NaCl_{70}$	$NaCl_{90}$
Arsenic (as As)	9.6	9.6	6.8	75.0	94.2	4.71	2.39
Selenium (as Se)	9.5	10.0	-	97.9	99.4	4.94	2.53
Sodium Cyanide (as HCN)	0.60	0.60	6.2	28.3	43.3	5.02	2.53
Potassium Tetracyanonickelate II (as HCN)	0.82	0.69	6.2	99.1	99.1	5.05	2.49
Nitrilo-Triacetic Acid (as H_3NTA)	13.0	12.0	-	99.5	>99.6	4.93	2.41

* Average Feed Concentration = (Feed Conc. + Concentrate Conc.)/2 in mg/L.
** Permeate Flux is $mL/hr \cdot cm^2$.

Arsenic and selenium solutions were prepared from 1000 mg/L atomic absorption standard solutions. Selenium was more effectively removed by all membranes than was arsenic. However, when a more selective membrane was employed, both metals were rejected very well and the differences between their extents of rejection decreased substantially.

The separation efficiencies of phenol and substituted phenols were strongly dependent on the type of membrane material employed. Table 5 compares the separation of phenols by cellulose acetate membrane in static cells and by aromatic polyamide fibres in a commercial module (DuPont ¼-size Permasep module, DuPont, 1972). When cellulose acetate membranes were used, essentially no separation was observed for phenol and p-chlorophenol. About 60% of naphthol was rejected and negative separation was obtained for p-cresol, i.e., solute concentration in the permeate was higher than that in

the corresponding feed solution. These poor separation characteristics have been reported by Matsuura and Sourirajan, 1971 and 1972, who proposed a criterion for RO separation of phenols and other organics whereby solute separation in RO is due to the preferential sorption of water on the membrane surface. This phenomenon is governed by the hydrogen-bonding ability of the organic molecule when it is essentially undissociated and by electrostatic repulsion of ions when the molecule is partially or completely dissociated.

TABLE 5. SEPARATION OF PHENOLS BY REVERSE OSMOSIS

Chemical	Ave. Feed Conc. (mg/L)		% Removal	
	$NaCl_{70}$	$NaCl_{90}$	$NaCl_{70}$	$NaCl_{90}$
Static Cells (Cellulose Acetate)				
Phenol	0.146	0.148	0	0
p-chlorophenol (as phenol)	0.260	0.260	0	7.7
Naphthol (as phenol)	0.038	0.038	62.7	57.3
p-cresol (as phenol)	0.012	0.015	-17.2	-66.7
¼-Size Permasep Module* (Aromatic Polyamide)				
Phenol		0.195		60.5
p-chlorophenol		0.032		62.5
Naphthol (as phenol)		0.042		75.4
p-cresol (as phenol)		0.057		59.5

* Average salt rejection = 91.2%, permeation rate = 0.034 L/s (0.45 lgpm,) water recovery = 46.9% operating at 2758 kPa (400 psi) and 25°C, (77°F) using 3500 mg/L NaCl solution (DuPont, 1972).

When aromatic polyamide fibres were used as the membrane material, the separation of all phenols increased to at least 60%. These rejections were consistent with those reported by Johnston and Lim, 1977.

Separation was reported to be affected by the molecular weight and steric size of the organic compounds (DuPont, 1972), but in the case of cellulose acetate there is no evident connection between solute separation and molecular weight of solute (Matsuura and Sourirajan, 1971 and 1972). However, the pH and dissociation constant strongly influence the solute separations by both membranes. The dissociation constant for phenol is small (pKa≃10) and consequently phenol exists essentially as molecules in solution and the separation is expected to decrease as the hydrogen-bonding ability of the molecule increases. As the pH of the solution is increased to 11, almost all the phenol dissociates and the separation increases sharply, up to 95% rejection for both cellulose acetate (Matsuura and Sourirajan, 1972) and polyamide (DuPont, 1972) membranes. At such a high pH, a polyamide membrane is more satisfactory than is cellulose acetate because of the rapid hydrolysis of a cellulosic membrane.

Results for the removals of chlorinated hydrocarbon and organic phosphate pesticides are summarized in Table 6. The experiments for various chemicals were conducted in the sequence listed in the table. As usual, a salt test was performed before treating the pesticide solution. At the end of the test, the static cell was rinsed with distilled water, followed by a permeation under pressure with distilled water to purge from the test cell any permeate left in the low pressure side. A constant amount of this "push out" solution was collected and termed residual in the present work. Residual concentration should be less than the permeate concentration in a normal RO process, where contamination and adsorption do not occur.

The persistent chemicals examined in the work were completely removed, except malathion, which was 79% and 93.5% removed by $NaCl_{70}$ and $NaCl_{90}$ membranes, respectively. However, many persistent organics are known to adsorb readily on polymeric membranes (Edwards and Schubert, 1974 and Hindin et al, 1969). Thus, the high removal efficiencies could be due to adsorption. Consequently, the actual removal efficiencies due to the RO process were unknown unless the contribution of adsorption to the observed overall membrane separation ability was determined. Abron (1972) reported that more than half of the DDT and aldrin were separated by sorption to the

TABLE 6. REJECTION OF CHLORINATED HYDROCARBON AND ORGANIC PHOSPHATE PESTICIDES BY REVERSE OSMOSIS

Run No.	Chemicals	Concentration (µg/L)						% Removal[3]		Remarks
		Feed	Concentrate		Permeate		Residual[2]			
			$NaCl_{70}$	$NaCl_{90}$	$NaCl_{70}$	$NaCl_{90}$	$NaCl_{70}$	$NaCl_{90}$	$NaCl_{70}$	$NaCl_{90}$	
1	Chlordane										
		12	0.7	0.5	0	0	0	0	100	100	
		13	1.1	0.9	0	0	0	0	100	100	
2	Endrin	18.3	5.0	5.1	0	0	0	0	100	100	Chlordane detected in concentrates
3	Parathion	2600	2000	1900	0.4	2.7	51	79	100	99.9	
4	Malathion	6200	5400	5200	1300	400	2900	900	79.0	93.5	
	Parathion[1]	0	0	0	290	280	240	220	-	-	
5	Aldrin	1.4	0	0	0	0	0	0	100	100	
	Malathion[1]	0	36	55	92	170	83	110	-	-	
	Parathion[1]	0	5	12	99	110	85	94	-	-	
6	P,P' -DDT	4.8	0.9	1.2	0	0	0	0	100	100)	Malathion, Parathion were detected
7	Aldrin	6.1	0.3	2.2	0	0	0	0	100	100)	
8	Purified Water										
	Malathion[1]	0	0.40	0.39	45	6.2	-	-	-	-	
	Parathion[1]	0	1.1	3.0	13	17	-	-	-	-	
	Aldrin[1]	0	0.07	0.08	0.25	0	-	-	-	-	
	Endrin[1]	0	0	0	0.29	0.15	-	-	-	-	

[1] Contamination from static cells.

[2] Solution in permeate side push out by the permeate from the distilled water run conducted immediately after the chemical run.

[3] Based on feed concentration, total removal by RO and by adsorption.

DuPont hollow polyamide fibres, and that the membrane characteristics were slightly, but adversely, altered by sorption of the pesticides. In the present work, the extent of adsorption to the membrane and/or the test cell apparatus (teflon coated stirrer) could not be measured. However, sorptions were obviously occurring in the system. Concentrations of the concentrate were consistently lower than that of the feed and yet little or no chemical was detected in the permeate. Apparently, the solute was "lost" due to adsorption on the membrane surface. The reappearance of chemicals as contamination in later experiments confirmed that previously adsorbed materials were dissolving with continued passage of permeate through the membrane. In runs 3 and 4, Table 6, the residual concentrations were higher than the permeate concentrations suggesting that adsorption first took place on top of a membrane and the adsorbed molecules migrated through the membrane and were eluted in the permeate as the membrane became saturated with the chemical. Thus, the separation of the chemicals was time dependent and tended to decline after a period of operation. This operative period decreased as the feed concentration increased. Consequently, reverse osmosis became an impractical process for removing these strongly sorbed substances from water. Perhaps the polymeric membrane material could be more opportunely employed as an adsorbent than as a physical membrane separation technique for these chemicals. Membrane separation characteristics have previously been reported by Abron (1972) to be slightly but adversely altered by sorption of the pesticides. However, in the present work, the salt rejection abilities of the membranes were found to be unchanged.

4.2 Pilot Plant

The RO pilot plant was on stream for approximately nine months. The general performance of the unit during the first four months has been presented by Johnston and Lim, 1977.

This Section will report the results obtained for the remaining five months of operation and will also present the results obtained in the heavy metal removal study carried out during the first four months of this program.

4.2.1 Analytical parameters

Basically, the same chemical parameters as in the first part of this study were examined in the present work. However, heavy metals were analysed instead of phosphates, nitrate and nitrite, and ammonia. As the metal concentrations in the secondary effluent were usually low, only eight could be routinely measured. These were: aluminum, cadmium, chromium, copper, iron, lead, manganese and zinc. In addition, four others: cobalt, magnesium, mercury and nickel, were measured in the spiked metal study. Analytical results are presented in Appendices A and B.

4.2.2 NaCl rejection tests

The salt rejection ability and permeation rate of the RO system using standard 2000 mg/L NaCl solutions are presented in Figure 5. Detailed performances of each individual module of the eight module system, during the first part of the study (April to July), have been presented by Johnston and Lim, 1977. After a one-month shut-down of the system, eight modules were employed up to October 10, after which only five were used. The frequency and the methods of membrane cleaning are marked on Figure 5. When the system was restarted after the one-month shut-down, little change was observed in the performance. During this shut-down, cold tap water was directed through the system at 0.075 to 0.15 L/s (1 to 2 Igpm) and minimal pressure. Thus, essentially no permeation occurred and membrane fouling was insignificant. The low water temperatures encountered may also have contributed to a reduced growth of bacteria on the membrane surface. If an extended shut-down period was anticipated, the membranes would probably have been stored submerged in a formaldehyde solution at pH of 4.5 to 5.

A gradual but significant reduction in overall rejection ability of the eight module pilot plant system was slowly became apparent by the time the unit was briefly shut down at the conclusion of the first part of this study. No dramatic increase in NaCl permeate concentration was observed if only the combined permeate was considered. However, this membrane failure had caused a sharp drop in the separation efficiencies of various constituents found in the secondary effluent. By monitoring individual modules, a defective $NaCl_{75}$ module was found and reduced performance of the other two $NaCl_{75}$ modules was noted.

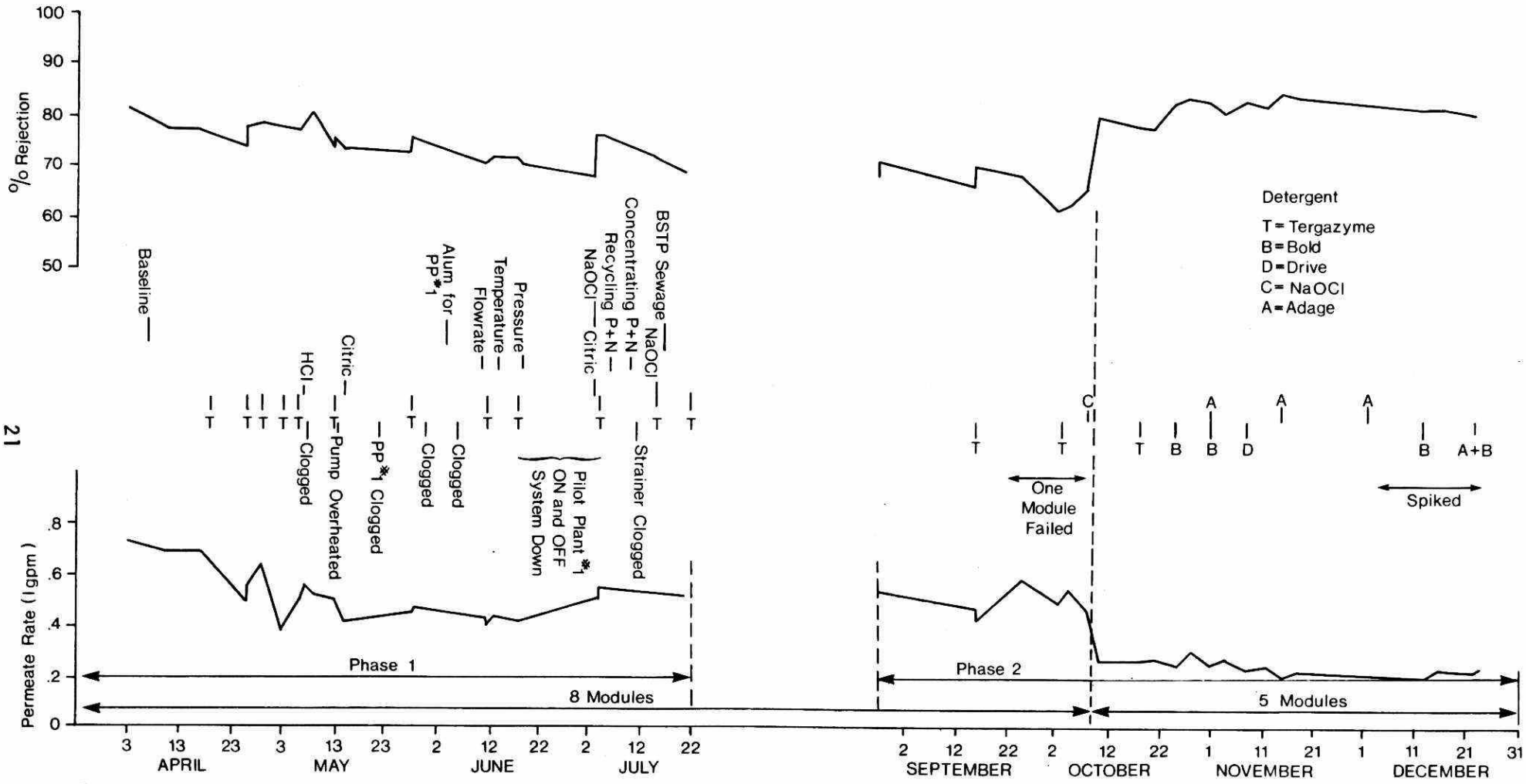


FIG.5 SODIUM CHLORIDE REJECTION AND PERMEATE FLUX vs DATE OF OPERATION

When only five $NaCl_{90}$ modules were used, the combined system performance was similar to that of a single $NaCl_{90}$ module (Johnston and Lim, 1977). It was relatively stable and showed little fluctuation due to membrane fouling or cleaning.

4.2.3 Solute separation efficiencies

The removal efficiencies for most of the constituents present in the secondary effluent were generally higher than the NaCl rejection from a standard solution under equivalent operating conditions. Johnston and Lim, 1977 presented the results of all chemical parameters examined in the first part of the program, except the heavy metals. Some of these results are plotted in Figure 6, along with the results obtained in the second part of the program. The measured percent rejection for TOC fluctuated between 70% and 99%. Most of this fluctuation was believed to be caused by the imprecision of the analytical technique, discussed by Johnston and Lim, 1977.

The percent rejections for total hardness, TDS, and Cl^- fluctuated very little and $SO_4^=$ ion was essentially constant. COD and TIC removals were more consistent than TOC, although not as stable as TDS. During membrane failure, some separations decreased to as low as 50%. The reductions of the measured organic and inorganic parameters were generally more serious than the reductions shown by the sodium chloride standard tests during the same period.

Data for suspended solids, colour, and turbidity, were not plotted in Figure 6. The low suspended solids concentrations in the feed, in conjunction with the detection limits of the gravimetric technique, prevented interpretable results from being obtained (e.g., all samples generally showed rejections >75%). In the high water recovery experiments (Section 4.2.4) suspended solids concentrations in the feed were substantially increased, but the permeate concentrations were still below the detection limit of 1.0 mg/L. Consequently, percent rejections were determinable only as >85% and no greater precision could be measured, although much higher separations were probably being achieved. In the few experiments in which suspended solids concentrations were unusually high in the secondary effluent, removal efficiencies above 95% were measured.

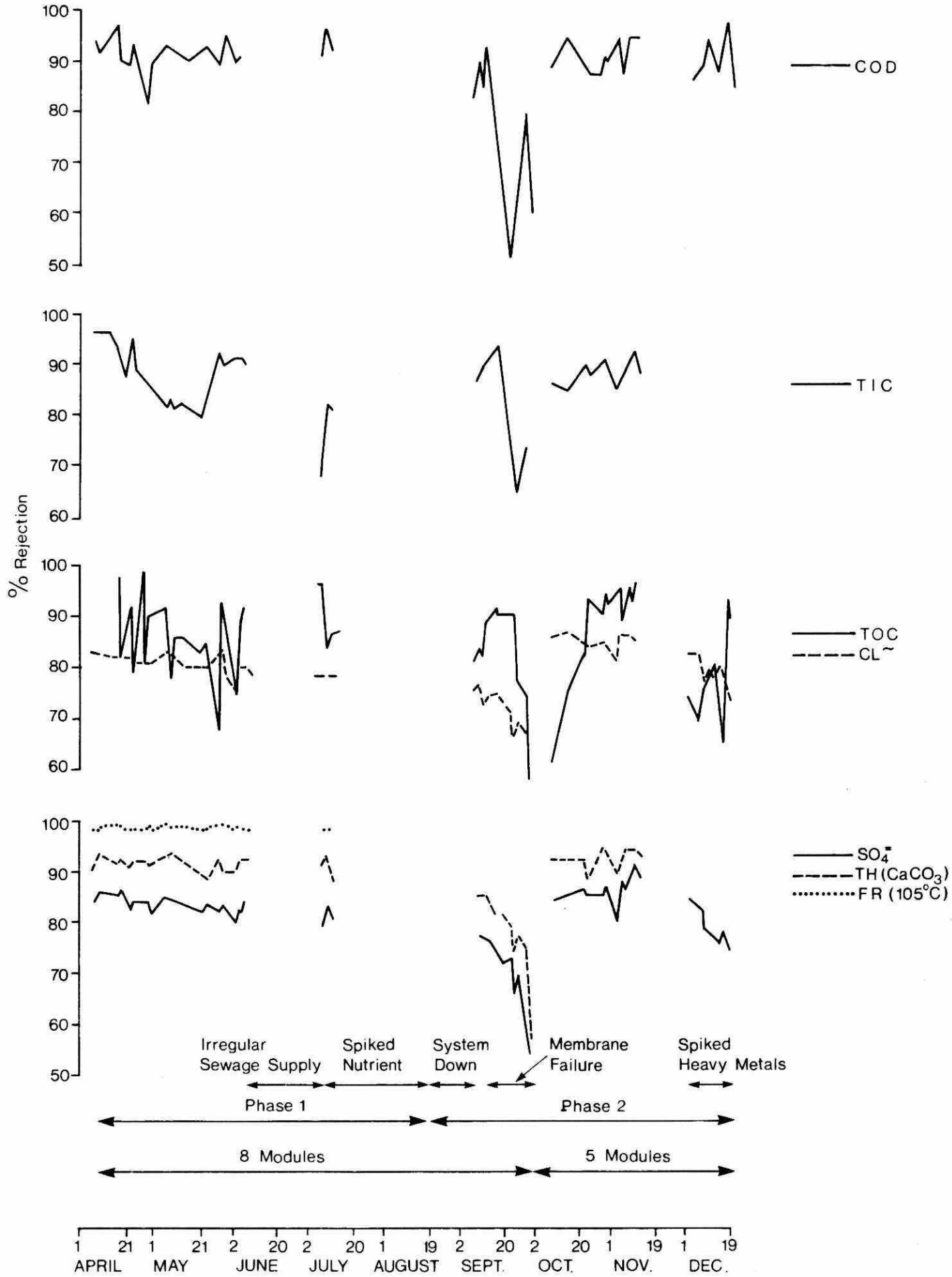


FIG.6 VARIATION OF REMOVAL EFFICIENCIES WITH TIME

All permeate samples appeared colourless and clean, although traces of turbidity (<0.5 JTU) were always reported, and colour was almost always less than five colour units (CU). The imprecision of the analytical techniques resulted in significant variations in the measurements of these parameters.

Heavy metal removals were generally more consistent and equal to or higher than those of the chemical constituents shown in Figure 6. Other metals, such as cadmium, chromium, lead and manganese, were too low in concentration (usually <0.001 mg/L) to provide any meaningful results. In fact, the percent rejections were the minimum values in many cases, because the permeate concentrations were lower than the detection limits of the atomic adsorption technique (0.001 mg/L).

All the heavy metal results, for this entire program, are summarized in Appendices A and B. For those metals present in the secondary effluent at extremely low concentrations, the laboratory static cell results and the results obtained in the spiked metal studies demonstrated that more than 95% metal removal could be achieved for either water or secondary effluent.

4.2.4 Permeation rates

Permeation rates of the RO system, based on the standard 2000 mg/L NaCl solution, have been presented in Figure 5. These fluxes gradually decreased with continued operation, but the most significant reduction occurred during the first month of the study. This initial decrease was due to the preferential fouling of the $NaCl_{75}$ membranes (Johnston and Lim, 1977). Thus, employment of membranes capable of high selectivity reduced surface fouling and permitted more reliable and consistent operation of the RO system. For example, when only five $NaCl_{90}$ modules were employed in the second part of this study, the permeation rates were relatively stable. The permeation rates of the treated effluent decreased in a manner analogous to that noted for the salt test. The effects of various operating conditions on permeate flux had been evaluated previously (Johnston and Lim, 1977) and in the second part, the RO unit was operated at the suggested optimal conditions. Feed flow rates generally affected membrane fouling and hence the permeation rate. Higher operating temperature and pressure also increased permeation. Fluxes were more sensitive to membrane fouling and cleaning than were separation efficiencies.

4.2.5 Effect of percent water recovery

In the first part of this study, almost all the experiments were conducted in a once-through operating mode (i.e., no recycling of the concentrate for further recovery of the water). The water recovery per pass, was less than 10% of the feed for the original eight module arrangement. However, in the second study, concentrate was partially returned to mix with the effluent so that water recovery of various levels could be obtained at a steady state condition.

Recovery levels of 12.5%, 25%, 50%, 75% and 85% were investigated and their effects on removal efficiencies are presented in Table 7.

TABLE 7. EFFECT OF CONCENTRATION ON REMOVAL EFFICIENCIES

Constituent	Percentage Removal (Range*)				
% Recovery	12.5%	25%	50%	75%	85%
TOC	57.1-90.0	85.7-93.7	92.8-95.8	88.5-97.5	95.5-98.0
TIC	83.9-86.7	91.1-91.8	83.3-88.4	85.1-92.1	87.8-93.2
TH	92.0-93.1	92.6-93.1	92.4-93.8	92.7-94.9	92.3-94.6
TDS	84.5-85.0	84.5-85.8	82.6-88.8	85.3-88.4	87.5-96.6
DFS	85.6-86.4	85.5-90.0	83.3-89.7	86.4-89.1	87.9-88.9
SS	>82.1->83.3	>80.8->86.1	>68.8->82.1	>86.8-90.7	>88.1->93.2
Cl^-	86.7-86.9	84.4-85.9	82.9-88.7	88.0-91.4	85.6-87.2
COD	92.0->97.5	84.0-94.9	83.3->98.3	84.0-94.8	93.5-96.6
Aluminum	91.7->99.4	98.3->99.5	96.8-99.4	99.5->99.6	99.1-99.7
Cadmium	81.8-91.7	>85.7->90.9	92.3-95.0	94.1-97.5	93.7-96.7
Chromium	96.5-97.0	>95.4-96.1	90.0->99.5	94.4-95.2	95.2-98.0
Copper	90.0	89.1-99.6	93.1-96.6	92.0-95.8	96.0-97.1
Iron	96.5->99.7	99.3-99.6	97.0-99.7	99.1-99.8	99.8-99.9
Lead	>75.0->87.5	>66.7->80.0	>66.7	>75.0	>75.0-90.0
Manganese	83.3-91.7	91.2-95.6	91.1-93.7	92.5-95.6	89.5-95.7
Zinc	83.3-85.0	95.4-96.8	87.5-95.3	95.8-96.7	96.0-97.8

* For 3 to 5 values.
Operating Conditions = 2068 kPa (300 psi), 27°C (80°F) and 0.6 L/s (8 lgpm) feed flow rate.

Neither removal efficiencies nor permeation rates were affected by the level of water recovery. Thus, it was conceivable that RO could be employed either as a concentrating, or separating, process. However, both the suspended and dissolved constituents in the effluent from the extended aeration pilot plant were low (Appendix A), so that even when concentrations up to sixfold were performed, the low feed solids did not significantly affect performance.

4.2.6 Flux drop and membrane cleaning

The observed declines in performance of the reverse osmosis system, especially permeate flux, were caused by fouling of the membrane surface, compaction of the porous substructure, and chemical degradation of the cellulose acetate membrane. The effects of operating conditions on the declining flux and reduced selectivity were discussed by Johnston and Lim, 1977. Similar observations were noted in the second part of this study, except that system performance was more consistent. As Figure 5 indicates, performance was reasonably consistent following the initial flux and selectivity changes during the first month of operation. During the second part of the study, all modules had reached a reasonably "stable" state, and any variabilities in performance were likely due to membrane fouling. Membranes with higher salt selectivity were less susceptible to this fouling than were low selectivity membranes, therefore, less fluctuation was observed in the second part, where the $NaCl_{90}$ membranes were employed almost exclusively. Membrane cleaning was routinely conducted and the frequency and cleaning chemicals used are marked in Figure 5. For removing surface foulants, enzyme active detergents were found to be most effective, although little difference was noted between various detergents. A series of washes with different solutions in conjunction with the necessary membrane relaxation cycles appears to be the most efficient cleaning approach. Membrane cleaning may thus restore most flux reductions caused by surface fouling of the RO membrane.

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APPENDIX A

Summary of Results for Effluent Treatment by Reverse Osmosis (Part 1)

Results for Pilot Plant Operation Using Only 5 $NaCl_{90}$ Modules (Part 2)

TABLE A-1. SUMMARY OF RESULTS FOR EFFLUENT TREATMENT BY REVERSE OSMOSIS (PART 1)

	50% Recycle			0.6 L/s, 2068 kPa			No Flow		
Date Time	Sept. 9/74 12:30 - 18:30			Sept. 9/74 18:30 - 1:00			Sept. 11/74 10:45 - 17:45		
Sample No.	Feed* 1	Perm* 2	% Rej.	Feed 3	Perm 4	% Rej.	Feed 5	Perm 6	% Rej.
pH	7.0			7.0			6.9		
TOC	5.0	<1.0	80.0	6.0	<1.0	>83.3	8.5	<1.0	>88.2
TIC	4.5	<1.0	77.8	6.0	<1.0	>83.3	8.0	<1.0	>87.5
TH ($CaCO_3$)	250	48.8	80.5	245	44.1	82.0	228	34.6	84.8
TDS	668	184.0	72.5	678	180	73.5	658	154	79.6
DFS	469	129	72.5	474	109	77.0	527	108	79.5
SS	2.8	<1.0	>64.3	3.2	<1.0	>68.8	3.2	<1.0	>68.8
Colour (CU)	20	5.0	75.0	20	5	75.0	20	5	75.0
Turb. (JTU)	0.9	0.2	77.8	0.9	0.2	77.8	1.3	0.2	84.6
Cl^-	148	35.2	76.2	146	35.2	75.9	116	26.6	77.1
$SO_4^=$	100	3.5	96.5	110	3.5	96.8	155	6.0	96.1
COD	18.0	3.5	80.6	17.5	2.5	85.7	19.5	1.5	92.3
Aluminum								<0.001	
Cadmium	0.018	0.003	83.3	0.017	0.003	82.4	0.019	0.002	89.5
Chromium								<0.001	
Cobalt									
Copper	0.03	0.003	90.0	0.03	0.001	96.7	0.03	0.002	93.3
Iron	0.10	0.03	70.0	0.16	0.010	93.8	0.16	0.001	99.4
Lead	0.002	<0.001	>50.0	0.002	0.001	50.0	0.002	0.002	0
Magnesium									
Manganese	0.013	0.005	61.5	0.010	0.004	60.0	0.006	0.002	66.7
Mercury									
Nickel									
Zinc	0.18	0.03	83.3	0.17	0.03	82.4	0.17	0.016	90.6

* All concentrations are in mg/L except colour, turbidity and pH.

Cont'd.../

TABLE A-1 (Cont'd). SUMMARY OF RESULTS FOR EFFLUENT TREATMENT BY REVERSE OSMOSIS (PART 1)

Date Time	Sept. 11/74 17:45 - 24:45			Sept. 11/74 24:45 - 7:45			Sept. 12/74 12:45 - 19:45		
Sample No.	Feed * 7	Perm * 8	% Rej.	Feed 9	Perm 10	% Rej.	Feed 11	Perm 12	% Rej.
pH	6.8			6.6			6.0		
TOC	6.0	<1.0	>83.3	7.0	<1.0	>85.7	4.0	<1.0	>75.0
TIC	9.0	<1.0	>88.9	7.5	<1.0	>86.7	7.0	<1.0	>85.7
TH ($CaCO_3$)	231	34.2	85.2	231	33.7	85.4	266	40.7	84.7
TDS	663	159	76.0	632	157	75.2	730	177	75.8
DFS	540	111	79.4	499	114	77.2	600	122	79.7
SS	3.6	<1.0	>72.2	3.6	<1.0	>72.2	6.4	<1.0	>84.4
Colour (CU)	10	5.0	50.0	10	5.0	50.0	10	<5.0	>50.0
Turb. (JTU)	1.2	0.2	83.3	0.5	0.2	60.0	2.5	0.3	88.0
Cl^-	125	27.8	77.8	121	30.2	75.0	140	39.2	72.0
$SO_4^=$	160	6.0	96.2	170	7.5	95.6	190	8.5	95.5
COD	18.8	2.1	88.8	18.0	1.0	94.4	20.4	3.0	85.3
Aluminum	<0.001				<0.001			<0.001	
Cadmium	0.02	0.003	85.0	0.03	0.004	86.7	0.03	0.006	80.0
Chromium		<0.001			<0.001			<0.001	
Cobalt									
Copper	0.03	0.003	90.0	0.03	0.003	90.0	0.03	0.003	90.0
Iron	0.16	0.002	98.8	0.16	0.002	98.8	0.25	0.002	99.2
Lead	0.001	0.001	0	0.001	0.001	0	0.002	0.001	50.0
Magnesium									
Manganese	0.008	0.003	62.5	0.03	0.005	83.3	0.06	0.010	83.3
Mercury									
Nickel									
Zinc	0.20	0.03	85.0	0.31	0.04	87.1	0.44	0.07	84.1

* All concentrations are in mg/L except colour, turbidity and pH.

Cont'd.../

TABLE A-1 (Cont'd). SUMMARY OF RESULTS FOR EFFLUENT TREATMENT BY REVERSE OSMOSIS (PART 1)

Date Time	Sept. 12/74 19:45 - 2:45			Sept. 12/74 2:45 - 9:45			Sept. 13/74 11:00 - 15:00		
Sample No.	Feed* 13	Perm* 14	% Rej.	Feed 15	Perm 16	% Rej.	Feed 17	Perm 18	% Rej.
pH	6.0			6.8			6.0		
TOC	10.0	<1.0	>90.0	6.5	<1.0	>84.6	9.0	<1.0	>88.9
TIC	6.0	<1.0	>83.3	6.0	<1.0	>83.3	6.0	<1.0	>83.3
TH ($CaCO_3$)	264	40.5	84.7	253	40.0	84.2	259	40	84.6
TDS	698	172	75.4	681	167	75.5	709	172	75.7
DFS	569	126	77.9	556	115	79.3	583	118	79.8
SS	5.2	<1.0	>80.8	6.0	<1.0	>83.3	6.8	<1.0	>85.3
Colour (CU)	10	5.0	50.0	10	5.0	50.0	10	<5.0	>50.0
Turb. (JTU)	1.7	0.3	82.4	1.6	0.3	81.2	1.8	0.2	88.9
Cl^-	136	37.4	72.5	143	36.4	74.5	149	40.6	72.8
$SO_4^=$	185	9.0	95.1	160	5.5	96.6	185	8.0	95.7
COD	21.1	4.5	78.7	20.5	3.2	84.4	19.5	1.2	93.8
Aluminum		<0.001			<0.001			<0.001	
Cadmium	0.03	0.005	83.3	0.03	0.005	83.3	0.03	0.004	86.7
Chromium		<0.001			<0.001			<0.001	
Cobalt									
Copper	0.03	0.003	90.0	0.03	0.002	93.3	0.03	0.003	90.0
Iron	0.22	0.001	99.5	0.24	0.001	99.6	0.31	<0.001	>99.7
Lead	0.002	0.002	0	0.003	0.001	66.7	0.002	0.001	50.0
Magnesium									
Manganese	0.06	0.013	78.3	0.06	0.011	81.7	0.05	0.009	82.0
Mercury									
Nickel									
Zinc	0.42	0.06	85.7	0.36	0.06	83.3	0.39	0.05	87.2

* All concentrations are in mg/L except colour, turbidity and pH.

Cont'd.../

TABLE A-1 (Cont'd). SUMMARY OF RESULTS FOR EFFLUENT TREATMENT BY REVERSE OSMOSIS (PART 1)

	←Once-Through 2413 kPa→			Sludge Wasting ←100% Recycling			0.3 L/s 2068 kPa→		
Date Time	Sept. 18/74 11:45 - 13:15			Sept. 19/74 15:00 - 23:00			Sept. 19/74 23:00 - 7:00		
Sample No.	Feed* 19	Perm* 20	% Rej.	Feed 21	Perm 22	% Rej.	Feed 23	Perm 24	% Rej.
pH	6.5			6.7			7.2		
TOC	6.5	0.5	92.3	9.5	0.5	94.7	4.0	0.5	87.5
TIC	8.0	0.5	93.8	6.5	<0.5	>92.3	7.0	<0.5	92.9
TH ($CaCO_3$)	220	42.9	90.5	214	44.9	79.0	218	40.9	81.2
TDS	610	166	72.8	567	165	70.9	578	156	73.0
DFS	463	114	75.4	430	116	73.0	439	110	74.9
SS	9.6	<1.0	>89.6	3.6	<1.0	72.2	4.8	1.2	75.0
Colour (CU)	5	5	0	5	5	0	5	5	0
Turb. (JTU)	3.2	0.4	87.5	0.9	0.2	77.8	1.2	0.4	66.7
Cl^-	155	39.0	74.8	145	40.0	72.4	145	38.5	73.4
$SO_4^=$	86	5.7	93.4	76	5.3	93.0	75	5.0	93.3
COD	24.0	4.3	82.1	4.8	19.2		15.5	9.1	41.3
Aluminum		<0.001			0.006			0.006	
Cadmium	0.019	0.002	89.5	0.013	0.002	84.6	0.009	0.001	88.9
Chromium		<0.001			0.001			0.001	
Cobalt									
Copper	0.03	0.002	93.3	0.03	0.005	83.3	0.03	0.005	83.3
Iron	0.48	<0.001	99.8	0.19	<0.001	>99.5	0.11	<0.001	>99.1
Lead	0.007	0.001	85.7	0.002	<0.001	>50.0	0.003	<0.001	>66.7
Magnesium									
Manganese	0.014	0.013	7.1	0.006	0.003	50.0	0.04	0.002	95.0
Mercury									
Nickel									
Zinc	0.27	0.03	88.9	0.15	0.03	80.0	0.08	0.018	77.5

* All concentrations are in mg/L except colour, turbidity and pH.

Cont'd.../

TABLE A-1 (Cont'd). SUMMARY OF RESULTS FOR EFFLUENT TREATMENT BY REVERSE OSMOSIS (PART 1)

Date Time	Sept. 19/74 7:00 - 15:00			Sept. 23/74 9:30 - 17:00			Sept. 23/74 17:00 - 1:00		
Sample No.	Feed* 25	Perm* 26	% Rej.	Feed 27	Perm 28	% Rej.	Feed 29	Perm 30	% Rej.
pH	7.5			6.9					
TOC	5.5	0.5	90.9	6.0	0.5	91.7	4.5	0.5	88.9
TIC	9.5	2.5	73.7	10.0	3.5	65.0	10.5	3.0	71.4
TH ($CaCO_3$)	217	40	81.6	207	42.7	79.4	209	41.3	80.2
TDS	594	151	74.6	523	135	74.2	515	138	73.2
DFS	434	93.6	78.4	371	79.2	78.7	372	80.4	78.4
SS	3.2	<1.0	>68.8	2.8	<1.0	>64.3	2.0	<1.0	>50.0
Colour (CU)	5	<5	> 0						
Turb. (JTU)	0.8	0.2	75.0						
Cl^-	147	36.5	75.2	120	33	72.5	118	32.5	72.5
$SO_4^=$	76	4.0	94.7	68	4.9	92.8	70	4.8	93.1
COD	27.8	7.2	74.1	11.5	6.7	41.7	9.6	4.8	50.0
Aluminum	0.11	0.005	95.5	0.06	0.004	93.3	0.06	0.008	86.7
Cadmium	0.007	0.001	85.7	0.008	0.001	87.5	0.006	<0.001	>83.3
Chromium		0.001			<0.001			<0.001	
Cobalt									
Copper	0.03	0.005	83.3	0.03	0.005	83.3	0.03	0.004	86.7
Iron	0.06	<0.001	98.3	0.34	<0.001	>99.7	0.07	<0.001	>98.6
Lead	0.002	<0.001	>50.0	0.004	0.001	75.0	0.001	<0.001	>0
Magnesium									
Manganese	0.006	0.002	66.7	0.009	0.002	77.8	0.005	0.002	60.0
Mercury									
Nickel									
Zinc	0.05	0.011	78.0	0.09	0.02	77.8	0.04	0.012	70.0

* All concentrations are in mg/L except colour, turbidity and pH.

Cont'd.../

TABLE A-1 (Cont'd). SUMMARY OF RESULTS FOR EFFLUENT TREATMENT BY REVERSE OSMOSIS (PART 1)

Date Time	Sept. 25/74 3:45 - 9:45			Sept. 25/74 9:45 - 14:45			Sept. 26/74 12:45 - 19:15		
Sample No.	Feed* 37	Perm* 38	% Rej.	Feed 39	Perm 40	% Rej.	Feed 41	Perm 42	% Rej.
pH	7.5			7.6			7.8		
TOC	6.0	0.5	91.7	6.0	1.0	83.3	7.0	1.5	78.6
TIC	12.5	4.5	64.0	12.5	4.5	64.0	14.0	4.0	71.4
TH ($CaCO_3$)	210	60	71.4	211	64.6	69.4	209	41.9	80.0
TDS	564	196	65.2	570	207	63.7	576	158	72.6
DFS	425	138	67.5	432	144	66.7	432	109	74.8
SS	1.2	<1.0	>16.7	1.6	<1.0	>37.5	2.0	<1.0	>50.0
Colour (CU)	5	<5	>0	5	<5	>0	5.0	<5.0	>0
Turb. (JTU)	0.3	0.2	33.3	0.4	0.2	50.0	1.1	0.2	81.8
Cl^-	141	47.5	66.3	136	50.0	63.2	144	38.0	73.6
$SO_4^=$	80	14.0	82.5	81	16.0	80.2	79	6.7	91.5
COD	6.7	5.8	13.4	11.5	5.8	49.6	11.5	4.8	58.3
Aluminum	0.12	0.02	83.3	0.14	0.03	78.6	0.10	0.014	86.0
Cadmium	0.004	0.001	75.0	0.004	0.001	75.0	0.006	<0.001	>83.3
Chromium		0.003			0.004			<0.001	
Cobalt									
Copper	0.02	0.007	65.0	0.03	0.008	73.3	0.03	0.006	80.0
Iron	0.009	<0.001	>88.9	0.007	<0.001	>85.7	0.20	0.001	99.5
Lead	0.005	<0.001	>80.0	0.001	<0.001	>0	0.002	<0.001	>50.0
Magnesium									
Manganese	0.001	0.001	0	0.001	0.001	0	0.004	0.001	75.0
Mercury									
Nickel									
Zinc	0.02	0.010	50.0	0.018	0.009	50.0	0.05	0.016	68.0

* All concentrations are in mg/L except colour, turbidity and pH.

Cont'd.../

TABLE A-1 (Cont'd). SUMMARY OF RESULTS FOR EFFLUENT TREATMENT BY REVERSE OSMOSIS (PART 1)

100% Recycle pH ≥ 7.5 Membrane losing selectivity ⟶

Date Time	Sept. 26/74 19:15 - 2:15			Sept. 26/74 2:15 - 9:15			Sept. 27/74 9:15 - 16:15		
Sample No.	Feed* 43	Perm* 44	% Rej.	Feed 45	Perm 46	% Rej.	Feed 47	Perm 48	% Rej.
pH	7.6			7.7			7.8		
TOC	5.0	1.5	70.0	6.5	1.0	84.6	6.5	1.5	76.9
TIC	14.0	4.0	71.4	13.5	4.5	66.7	13.0	4.5	65.4
TH ($CaCO_3$)	211	45.3	78.5	213	55.7	73.8	212	61.8	70.8
TDS	586	170	71.0	585	190	67.5	578	207	64.2
DFS	444	116	73.9	444	149	66.4	458	147	67.9
SS	1.6	<1.0	>37.5	1.2	<1.0	>16.7	1.2	<1.0	>16.7
Colour (CU)	5	5	0	5	<5	>0	10	5	50.0
Turb. (JTU)	0.4	0.3	25.0	0.3	0.2	33.3	0.2	0.1	50.0
Cl^-	145	42.0	71.0	147	48.0	67.3	145	50	65.5
$SO_4^=$	80	6.5	91.9	81	0.2	99.8			
COD	14.4	1.5	89.6	24.0	5.5	77.1	16.0	3.0	81.2
Aluminum	0.14	0.019	86.4	0.14	0.02	85.7	0.22	0.05	77.3
Cadmium	0.003	<0.001	>66.7	0.004	0.001	75.0	0.005	0.001	80.0
Chromium		0.001			0.001		0.02	0.002	90.0
Cobalt									
Copper	0.03	0.005	83.3	0.04	0.007	82.5	0.05	0.008	84.0
Iron	0.05	<0.001	>98.0	0.018	<0.001	>94.4	0.03	0.001	96.7
Lead	0.001	<0.001	>0	0.001	<0.001	>0	0.001	<0.001	>0
Magnesium									
Manganese	0.004	0.002	50.0	0.004	0.002	50.0	0.002	0.006	
Mercury									
Nickel									
Zinc	0.03	0.008	73.3	0.018	0.007	61.1	0.018	0.008	55.6

* All concentrations are in mg/L except colour, turbidity and pH.

Cont'd.../

TABLE A-1 (Cont'd). SUMMARY OF RESULTS FOR EFFLUENT TREATMENT BY REVERSE OSMOSIS (PART 1)

← 100% Recycling pH ≥ 7.5 Membrane failed

Date Time	Sept. 30/74 10:00 - 17:30			Sept. 30/74 17:30 - 1:30			Sept. 30/74 1:30 - 9:30		
Sample No.	Feed* 49	Perm* 50	% Rej.	Feed 51	Perm 52	% Rej.	Feed 53	Perm 54	% Rej.
pH	7.5			7.7			7.7		
TOC	6.5	2.5	61.5	5.0	1.0	80.0	7.5	1.5	80.0
TIC	14.5	3.5	75.9	15.0	4.0	73.3	15.0	5.0	66.7
TH ($CaCO_3$)	212	47.2	77.7	220	55.1	75.0	222	72.2	67.5
TDS	497	153	69.2	531	170	68.0	536	201	62.5
DFS	404	98.4	75.6	413	112	72.9	413	141	65.9
SS	2.0	<1.0	>50.0	<1.0	<1.0	>0	<1.0	<1.0	>0
Colour (CU)	10	5	50.0	10	5	50.0	10	5	50.0
Turb. (JTU)	0.5	0.3	40.0	0.5	0.1	80.0	0.5	0.2	60.0
Cl^-	100	31	69.0	105	35	66.7	115	45	60.9
$SO_4^=$									
COD	20.0	2.5	87.5	16.0	4.5	71.9	16.0	2.0	87.5
Aluminum	0.21	0.02	90.5	0.20	0.03	85.0	0.21	0.04	81.0
Cadmium	0.005	0.001	80.0	0.002	0.001	50.0	0.003	0.002	33.3
Chromium	0.005	0.001	80.0	0.005	0.001	80.0	0.002	0.002	0
Cobalt									
Copper	0.05	0.007	86.0	0.05	0.009	82.0	0.05	0.009	82.0
Iron	0.25	0.001	99.6	0.06	<0.001	>98.3	0.015	<0.001	93.3
Lead	0.001	0.001	0	0.001	<0.001	>0	0.001	0.002	
Magnesium									
Manganese	0.008	0.002	75.0	0.006	0.002	66.7	0.005	0.002	60.0
Mercury									
Nickel									
Zinc	0.06	0.013	78.3	0.02	0.007	65.0	0.014	0.007	50.0

* All concentrations are in mg/L except colour, turbidity and pH.

Cont'd.../

TABLE A-1 (Cont'd). SUMMARY OF RESULTS FOR EFFLUENT TREATMENT BY REVERSE OSMOSIS (PART 1)

Date Time	Oct. 1/74 9:30 - 15:30			Oct. 1/74 15:30 - 21:30		
Sample No.	Feed* 55	Perm* 56	% Rej.	Feed 57	Perm 58	% Rej.
pH	6.9			6.9		
TOC	5.5	3.0	45.5	6.0	2.0	66.7
TIC	14.5	6.5	55.2	9.0	4.0	55.6
TH ($CaCO_3$)	225	91.9	59.2	225	103	54.2
TDS	545	248	54.5	578	278	51.9
DFS	421	181	57.0	442	205	53.6
SS	2.4	1.0	58.3	1.0	1.0	0
Colour (CU)	10	5	50.0	10	5	50.0
Turb. (JTU)	0.7	0.3	57.1	0.3	0.1	66.7
Cl^-	115	50	56.5	135	70	48.1
$SO_4^=$						
COD	16.0	6.5	59.4	20.5	7.5	63.4
Aluminum	0.28	0.25	82.1	0.11	0.005	95.5
Cadmium	0.003	0.002	33.3	0.006	0.003	50.0
Chromium	0.001	0.001	0	0.004	0.001	75.0
Cobalt						
Copper	0.04	0.010	75.0	0.06	0.016	73.3
Iron	0.012	0.001	91.7	0.03	0.001	96.7
Lead	0.001	0.001	0	0.001	0.001	0
Magnesium						
Manganese	0.005	0.003	40.0	0.008	0.005	37.5
Mercury						
Nickel						
Zinc	0.014	0.010	28.6	0.05	0.04	20.0

* All concentrations are in mg/L except colour, turbidity and pH.

Cont'd.../

TABLE A-1. RESULTS FOR PILOT PLANT OPERATION USING ONLY 5 $NaCl_{90}$ MODULES (PART 2)

←50% Recycling	0.6 L/s	2068 kPa →

Date Time	Oct. 10/74 11:00 - 18:30			Oct. 10/74 18:30 - 2:30			Oct. 10/74 2:30 - 9:00		
Sample No.	Feed* 59	Perm* 60	% Rej.	Feed 61	Perm 62	% Rej.	Feed 63	Perm 64	% Rej.
pH	6.9			6.9			6.9		
TOC	6.0	2.0	66.7	6.0	3.0	50.0	6.5	2.0	69.2
TIC	8.0	1.5	81.2	10.0	1.5	85.0	11.0	1.5	86.4
TH ($CaCO_3$)	226	18.3	91.9	226	17.1	92.4	219	15.5	92.9
TDS	622	92.8	85.1	667	94.8	85.8	666	93.2	86.0
DFS	539	72.8	86.5	578	72.4	87.5	570	73.2	87.2
SS	<1.0	1.6		1.6	<1.0	>37.5	2.4	<1.0	>58.3
Colour (CU)	10	5	50.0	10	5	50.0	10	5	50.0
Turb. (JTU)	0.3	0.4		0.4	0.2	50.0	0.4	0.1	75.0
Cl^-	135	19	85.9	140	19	86.4	135	17	87.4
$SO_4^=$									
COD	19.5	1.5	92.3	22.0	2.5	88.6	22.0	3.0	86.4
Aluminum	0.09	<0.001	>98.9	0.11	<0.001	>99.1	0.11	0.003	97.3
Cadmium	0.015	0.002	86.7	0.016	0.002	87.5	0.015	0.002	86.7
Chromium	0.011	0.001	90.9	0.014	<0.001	>92.9	0.011	<0.001	>90.9
Cobalt									
Copper	0.03	0.003	90.0	0.03	0.003	90.0	0.03	0.004	86.7
Iron	0.15	<0.001	>99.3	0.14	0.001	99.3	0.20	0.001	99.5
Lead	0.004	<0.001	75.0	0.008	<0.001	>87.5	0.001	0.001	0
Magnesium									
Manganese	0.013	0.002	84.6	0.014	0.002	85.7	0.013	0.001	92.3
Mercury									
Nickel									
Zinc	0.28	0.04	85.7	0.28	0.04	85.7	0.24	0.03	87.5

* All concentrations are in mg/L except colour, turbidity and pH.

Cont'd.../

TABLE A-1 (Cont'd). RESULTS FOR PILOT PLANT OPERATION USING ONLY 5 $NaCl_{90}$ MODULES (PART 2)

← 12.5% Recovery — 0.6 L/s 3068 kPa →

Date Time	Oct. 16/74 12:30 - 20:00			Oct. 16/74 20:00 - 4:00			Oct. 17/74 4:00 - 12:00		
Sample No.	Feed* 65	Perm* 66	% Rej.	Feed 67	Perm 68	% Rej.	Feed 69	Perm 70	% Rej.
pH	7.1			7.1			7.0		
TOC	8.5	1.5	82.4	10.5	4.5	57.1	10.0	1.0	90.0
TIC	15.0	2.0	86.7	15.5	2.5	83.9	15.5	2.5	83.9
TH ($CaCO_3$)	219	17.5	92.0	212	15.7	92.6	216	14.8	93.1
TDS	662	100	83.9	675	101	85.0	664	103	84.5
DFS	541	75.6	86.0	562	76.4	86.4	567	81.6	85.6
SS	5.6	<1.0	>82.1	6.0	1.0	>83.3	6.0	<1.0	>83.3
Colour (CU)	20	5	75.0	15	5	66.7	20	5	75.0
Turb. (JTU)	0.7	0.1	85.7	0.8	0.2	75.0	0.7	0.2	71.4
Cl^-	135	18	86.7	135	18	86.7	145	19	86.9
$SO_4^=$									
COD	19.9	<0.5	>97.5	17.2	<0.5	>97.1	20.1	1.6	92.0
Aluminum	0.12	0.01	91.7	0.14	<0.001	>99.3	0.18	<0.001	>99.4
Cadmium	0.011	0.002	81.8	0.011	0.001	90.9	0.012	0.001	91.7
Chromium	0.20	0.007	96.5	0.10	0.003	97.0	0.06	0.002	96.7
Cobalt									
Copper	0.03	0.003	90.0	0.03	0.003	90.0	0.03	0.003	90.0
Iron	0.23	0.008	96.5	0.27	<0.001	>99.6	0.37	<0.001	>99.7
Lead	0.001	<0.001	>0	0.008	<0.001	>87.5	0.004	<0.001	>75.0
Magnesium									
Manganese	0.006	0.001	83.3	0.010	0.001	90.0	0.012	0.001	91.7
Mercury									
Nickel									
Zinc	0.12	0.02	83.3	0.12	0.019	84.2	0.12	0.018	85.0

* All concentrations are in mg/L except colour, turbidity and pH.

Cont'd.../

TABLE A-1 (Cont'd). RESULTS FOR PILOT PLANT OPERATION USING ONLY 5 $NaCl_{90}$ MODULES (PART 2)

←——25% Recovery 0.6 L/s 2068 kPa ——→

Note: Tap Water entering holding tank

Date Time	Oct. 23/74 12:00 - 18:30			Oct. 23/74 18:30 - 1:30			Oct. 24/74 1:30 - 8:30		
Sample No.	Feed* 71	Perm* 72	% Rej.	Feed 73	Perm 74	% Rej.	Feed 75	Perm 76	% Rej.
pH									
TOC	3	0.5	83.3	2	2.5		1	1	
TIC	18	2	88.9	19	1.5	92.1	19	1.5	92.1
TH ($CaCO_3$)	146	13.2	91.0	147	11.8	92.0	146	11	92.5
TDS	266	40.8	84.7	278	33.6	87.9	275	35.2	87.2
DFS	216	27.6	87.2	227	27.6	87.8	230	27.6	88.0
SS	7.2	1	86.1	3.2	1	68.8	2.8	1	64.3
Colour (CU)	5	5	0	5	5	0	5	5	0
Turb. (JTU)	2	0.4	80	1.5	0.2	86.7	1	0.2	80
Cl^-	53	8.3	84.3	55	7.5	86.4			
$SO_4^=$									
COD	20.6	4.2	79.6				10.7	1.6	85.0
Aluminum	0.28	0.004	99.3	0.22	0.001	99.5	0.23	0.003	98.7
Cadmium	0.004	0.001	75	0.002	0.001	50	0.003	0.001	66.7
Chromium	0.017	0.001	94.1	0.012	0.001	91.7	0.018	0.001	94.4
Cobalt									
Copper									
Iron	0.35	0.001	99.7	0.13	0.001	99.2	0.07	0.001	98.6
Lead	0.002	0.001	50	0.016	0.001	97.1	0.001	0.001	
Magnesium									
Manganese	0.012	0.001	91.7	0.006	0.001	83.3	0.002	0.001	50
Mercury									
Nickel									
Zinc	0.09	0.004	95.6	0.05	0.002	96	0.04	0.002	95

* All concentrations are in mg/L except colour, turbidity and pH.

Cont'd.../

TABLE A-1 (Cont'd). RESULTS FOR PILOT PLANT OPERATION USING ONLY 5 $NaCl_{90}$ MODULES (PART 2)

	←50% Recovery			0.6 L/s			2068 kPa →		
Date Time	Oct. 24/74 12:30 - 18:30			Oct. 24/74 18:30 - 1:30			Oct. 25/74 1:30 - 8:30		
Sample No.	Feed* 77	Perm* 78	% Rej.	Feed 79	Perm 80	% Rej.	Feed 81	Perm 82	% Rej.
pH									
TOC	6.5	0.5	>92.3	8.0	0.5	93.7	9.5	0.5	94.7
TIC	15.5	2	87.1	15	2	86.6	17.5	2.5	85.5
TH ($CaCO_3$)	211	26	87.6	210	25.8	87.7	205	28.5	86.1
TDS	615	132	78.5	635	138	78.2	641	162	74.7
DFS	512	108	78.9	547	111	79.7	556	129	76.8
SS	6	1	83.3	6	1	83.3	6.4	1	84.3
Colour (CU)	10	5	>50	10	5	>50	10	<5	>50
Turb. (JTU)	2.5	0.2	92	2.4	0.3	87.5	2.4	0.3	87.5
Cl^-	132	26	80.3	132	26	80.3	132	32	75.7
$SO_4^=$									
COD	25	2.5	90	22.6	4.5	80.0	22	1.2	94.6
Aluminum	0.14	0.022	84.2	0.14	0.003	97.8	0.16	0.004	97.5
Cadmium	0.012	0.001	>91.7	0.014	0.001	>92.8	0.013	0.001	92.3
Chromium	0.027	0.001	>96.3	0.025	0.001	>96.0	0.018	0.001	>94.4
Cobalt									
Copper	0.039	0.003	92.3	0.038	0.002	94.7	0.036	0.003	91.6
Iron	0.35	0.024	93.1	0.32	0.001	99.6	0.34	0.004	98.8
Lead	0.006	0.001	83.3	0.003	0.001	66.6	0.003	<0.001	>66.7
Magnesium									
Manganese	0.025	0.002	92	0.023	0.001	95.6	0.035	<0.002	>94.3
Mercury									
Nickel									
Zinc	0.18	0.003	98.3	0.19	0.009	95.2	0.17	0.009	94.7

* All concentrations are in mg/L except colour, turbidity and pH.

Cont'd.../

TABLE A-1 (Cont'd). RESULTS FOR PILOT PLANT OPERATION USING ONLY 5 $NaCl_{90}$ MODULES (PART 2)

	←25% Recovery			2413 kPa →					
Date Time	Oct. 30/74 11:45 - 6:15			Oct. 30/74 6:15 - 1:15			Oct. 31/74 1:15 - 8:15		
Sample No.	Feed * 83	Perm * 84	% Rej.	Feed 85	Perm 86	% Rej.	Feed 87	Perm 88	% Rej.
pH									
TOC	6.5	0.5	92.3	8	0.5	93.7	7	1	85.7
TIC	18.5	1.5	91.8	18.5	1.5	91.8	17	1.5	91.1
TH ($CaCO_3$)	208	15.2	92.6	212	14.6	93.1	214	14.6	93.1
TDS	671	99.2	85.2	629	97.2	84.5	662	94	85.8
DFS	590	58.8	90.0	552	79.6	85.5	588	70.4	88.0
SS	5.2	<1	>80.8	7.2	<1.0	>86.1	6.4	<1	>84.3
Colour (CU)	10	<5	>50	10	<5	>50	10	<5	>50
Turb. (JTU)	1.7	0.2	88.2	2.6	0.2	92.3	2.2	0.2	90.9
Cl^-	135	21	84.4	148	21	85.8	149	21	85.9
$SO_4^=$									
COD	20	3.2	84.0	26.8	4	85.0	39.2	2	94.9
Aluminum	0.18	0.003	98.3	0.22	<0.001	>99.5	0.19	<0.001	>99.4
Cadmium	0.007	<0.001	>85.7	0.01	<0.001	>90	0.011	<0.001	>90.9
Chromium	0.026	0.001	96.1	0.03	0.001	96.6	0.022	0.011	95.4
Cobalt									
Copper	0.64	0.002	99.6	0.051	0.003	94.1	0.037	0.004	89.1
Iron	0.3	0.002	99.3	0.64	0.002	99.6	0.44	0.002	99.5
Lead	0.003	<0.001	>66.7	0.005	<0.001	>80	0.004	<0.001	>75.0
Magnesium									
Manganese	0.023	0.001	95.6	0.075	0.004	94.6	0.057	0.005	91.2
Mercury									
Nickel									
Zinc	0.087	0.004	95.4	0.016	0.005	96.8	0.15	0.005	96.4

* All concentrations are in mg/L except colour, turbidity and pH.

Cont'd.../

TABLE A-1 (Cont'd). RESULTS FOR PILOT PLANT OPERATION USING ONLY 5 $NaCl_{90}$ MODULES (PART 2)

	←75% Recovery				2068 kPa→							
Date Time	Oct. 31/74 11:45 - 18:15				Oct. 31/74 18:15 - 1:15				Nov. 1/74 1:15 - 8:15			
Sample No.	Feed * 89	Conc * 95	Perm * 90	% Rej.	Feed 91	Conc 96	Perm 92	% Rej.	Feed 93	Conc 97	Perm 94	% Rej.
pH	7.5	14	0.5	96.4	7.5	18.5	0.5	97.3	11	19	1.5	92.1
TOC	13.5	27.5	2	92.7	13.5	36.5	2.5	93.1	14.5	40	2.5	93.8
TIC	219	391	24.8	93.6	219	614	34	94.4	219	694	36	94.8
TH ($CaCO_3$)	666	981	147	85.0	686	1670	210	87.4	684	1880	217	88.4
TDS	564	846	110	87.0	582	1460	166	88.6	586	1650	180	89.1
DFS	3.2	6	1	83.3	3.6	6	1	83.3	6.0	5.2	<1	>80.8
SS	5	20	<5	>75.0	5	40	<5	>87.5	5	40	<5	>87.5
Colour (CU)	1.2	2.2	0.2	90.9	1.6	2.2	0.2	90.9	2.2	1.8	0.4	77.8
Turb. (JTU)	147	240	32	86.6	143	360	48	86.6	144	390	55	85.9
Cl^-												
$SO_4^=$	19.6	35.6	2.5	92.9	19.6	46.8	4	91.4	22.0	54	5	92.6
COD	0.18	0.16	0.002	98.7	0.15	0.19	0.003	98.4	0.17	0.19	0.005	97.3
Aluminum	0.011	0.013	<0.001	92.3	0.013	0.021	<0.001	>95.2	0.012	0.026	0.001	96.2
Cadmium	0.022	0.03	<0.001	96.6	0.020	0.043	0.001	97.6	0.026	0.033	0.001	96.9
Chromium												
Cobalt	0.033	0.066	0.003	95.4	0.030	0.11	0.007	93.6	0.037	0.11	0.006	94.5
Copper	0.26	0.34	0.003	99.1	0.28	0.29	0.004	98.6	0.41	25	0.009	96.4
Iron	0.003				0.003	0.007	0.001	85.7	0.004	0.004	0.001	75.0
Lead												
Magnesium	0.032	0.07	0.003	95.7	0.038	0.078	0.009	88.4	0.039	0.09	0.004	95.6
Manganese												
Mercury												
Nickel	0.18	0.16	0.011	93.1	0.19	0.21	0.01	95.2	0.20	0.25	0.01	96.0
Zinc												

* All concentrations are in mg/L except colour, turbidity and pH.

Cont'd.../

TABLE A-1 (Cont'd). RESULTS FOR PILOT PLANT OPERATION USING ONLY 5 $NaCl_{90}$ MODULES (PART 2)

	← 50% Recovery/Recycling			0.6 L/s			2413 kPa →		
Date Time	Nov. 1/74 11:45 - 18:15			Nov. 1/74 18:15 - 1:15			Nov. 2/74 1:15 - 8:15		
Sample No.	Feed* 99	Perm* 100	% Rej.	Feed 101	Perm 102	% Rej.	Feed 103	Perm 104	% Rej.
pH									
TOC	7	0.5	92.8	7	0.5	92.8	8	<0.5	>93.8
TIC	10	1.5	85	9	1.5	83.3	13	1.5	88.4
TH ($CaCO_3$)	224	15.7	92.9	225	17.5	92.2	215	16.3	92.4
TDS	671	101	84.9	691	120	82.6	678	118	82.6
DFS	575	78.8	86.2	607	95.6	84.2	603	101	83.2
SS	5.6	<1.0	>82.1	4.4	<1	>77.3	3.2	<1	>68.8
Colour (CU)	10	<5	>50	10	<5	>50.0	5	<5	> 0.0
Turb. (JTU)	1.5	0.2	86.6	1.4	0.2	85.7	1.3	0.2	84.6
Cl^-	142	21	85.2	147	25	82.9	135	23	82.9
$SO_4^=$									
COD	21	2	90.4	21.6	3.6	83.3	21.6	<0.5	>97.6
Aluminum	0.16	0.002	98.7	0.15	0.003	98.0	0.16	0.005	96.8
Cadmium	0.013	<0.001	>92.3	0.013	0.001	92.3	0.015	<0.001	>93.3
Chromium	0.022	<0.001	>95.4	0.22	<0.001	>99.5	0.018	<0.001	>94.4
Cobalt									
Copper	0.029	0.002	93.1	0.029	0.002	93.1	0.029	0.001	96.6
Iron	0.036	0.004	98.8	0.27	0.006	97.8	0.3	0.009	97.0
Lead	0.003	<0.001	>66.7	0.003	<0.001	>66.7	0.003	<0.001	>66.6
Magnesium									
Manganese	0.039	0.003	92.3	0.036	0.003	91.6	0.045	0.04	91.1
Mercury									
Nickel									
Zinc	0.22	0.013	94.0	0.19	0.013	93.2	0.26	0.012	95.3

* All concentrations are in mg/L except colour, turbidity and pH.

Cont'd.../

TABLE A-1 (Cont'd). RESULTS FOR PILOT PLANT OPERATION USING ONLY 5 $NaCl_{90}$ MODULES (PART 2)

	←75% Recovery			2413 kPa→		
Date Time	Nov. 4/74 16:00 - 1:00			Nov. 5/74 1:00 - 10:00		
Sample No.	Feed * 105	Perm * 106	% Rej.**	Feed 107	Perm 108	% Rej.**
pH						
TOC	9	0.5	94.4	7.5	0.5	93.3
TIC	7	1.5	78.6	7	1.5	78.6
TH ($CaCO_3$)	227	34.4	84.8	221	39.4	82.1
TDS	637	167	73.8	659	208	68.4
DFS	472	110	76.6	498	150	69.8
SS	6	<1	>83.3	4.8	<1	>79.1
Colour (CU)	5	<5	>0	5	<5	>0
Turb. (JTU)	2.2	0.3	86.3	1.6	0.3	81.2
Cl^-	145	34	76.6	152	47	69.0
$SO_4^=$						
COD	21	0.8	96.1	18.8	1.2	93.6
Aluminum	0.16	0.002	98.8	0.14	0.001	99.2
Cadmium	0.017	<0.001	>94.1	0.017	0.001	94.1
Chromium	0.022	0.001	95.4	0.015	0.002	86.6
Cobalt						
Copper	0.034	0.005	85.2	0.029	0.004	86.2
Iron	0.42	0.002	99.5	0.36	0.002	99.4
Lead	0.003	<0.001	>66.7	0.003	<0.001	>66.7
Magnesium						
Manganese	0.058	0.009	84.4	0.066	0.009	86.3
Mercury						
Nickel						
Zinc	0.32	0.11	96.5	0.32	0.022	93.1

* All concentrations are in mg/L except colour, turbidity and pH.

** Based on feed instead of concentrate.

Cont'd.../

TABLE A-1 (Cont'd). RESULTS FOR PILOT PLANT OPERATION USING ONLY 5 $NaCl_{90}$ MODULES (PART 2)

	←75% Recovery				2413 kPa →			
Date Time	Nov. 5/74 15:00 - 23:30				Nov. 6/74 23:30 - 8:00			
Sample No.	Feed * 109	Conc * 113	Perm * 110	% Rej.	Feed 111	Conc 114	Perm 112	% Rej.
pH								
TOC	6.5	15	0.5	96.6	6.5	20	0.5	97.5
TIC	6.0	15	1.5	90.0	6.5	19	1.5	92.1
TH ($CaCO_3$)	223	539	39	92.7	223	731	37	94.9
TDS	676	1390	175	87.4	674	1850	214	88.4
DFS	516	1160	128	88.9	532	1560	170	89.1
SS	3.6	7.6	<1	>86.8	4.8	9.2	1	89.1
Colour (CU)	5	20	<5	>75.0	5	30	<5	>83.3
Turb. (JTU)	1.0	2.5	0.3	88.0	1.2	2.3	0.2	91.3
Cl^-	159	350	30	91.4	163	460	55	88.0
$SO_4^=$								
COD	16.8	38.8	2	94.8	20	57.2	3.6	93.7
Aluminum	0.14	0.26	<0.001	>99.6	0.14	0.21	0.001	99.5
Cadmium	0.017	0.034	0.001	97.0	0.017	0.041	0.001	97.5
Chromium	0.011	0.018	0.001	94.4	0.014	0.021	0.001	95.2
Cobalt								
Copper	0.025	0.09	0.006	93.3	0.027	0.12	0.005	95.8
Iron	0.32	0.43	0.002	99.5	0.37	0.43	0.001	99.8
Lead	0.003	0.004	<0.001	>75.0	0.004	0.004	<0.001	>75.0
Magnesium								
Manganese	0.072	0.16	0.007	95.6	0.075	0.21	0.01	95.2
Mercury								
Nickel								
Zinc	0.33	0.5	0.021	95.8	0.30	0.58	0.019	96.7

* All concentrations are in mg/L except colour, turbidity and pH.

Cont'd.../

TABLE A-1 (Cont'd). RESULTS FOR PILOT PLANT OPERATION USING ONLY 5 $NaCl_{90}$ MODULES (PART 2)

	←50% Recovery				2413 kPa→			
Date Time	Nov. 6/74 13:30 - 22:30				Nov. 7/74 22:30 - 7:30			
Sample No.	Feed* 115	Conc* 119	Perm* 116	% Rej.	Feed 117	Conc 120	Perm 118	% Rej.
pH								
TOC	6.5	11.5	0.5	95.6	9.0	12	0.5	95.8
TIC	3.6	7	1	85.7	5.0	8	1	87.5
TH ($CaCO_3$)	233	417	25.6	93.8	225	404	25.2	93.7
TDS	680	1330	148	88.8	638	1090	141	87.0
DFS	540	1050	108	89.7	501	886	106	88.0
SS	4.8	5.6	<1	>82.1	6.8	4.8	<1	>79.1
Colour (CU)	5	10	<5	>50.0	5	10	<5	>50.0
Turb. (JTU)	1.3	1.6	0.2	87.5	1.5	1.5	0.2	86.6
Cl^-	166	280	32	88.5	173	276	31	88.7
$SO_4^=$								
COD	18.0	27.6	<0.5	>98.1	18.4	30.8	<0.5	>98.3
Aluminum	0.12	0.17	0.001	99.4	0.15	0.14	0.001	99.2
Cadmium	0.024	0.039	0.002	94.8	0.022	0.04	0.002	95.0
Chromium	0.012	0.01	0.001	90.0	0.010	0.007	0.001	85.7
Cobalt								
Copper	0.027	0.064	0.004	93.7	0.030	0.066	0.005	92.4
Iron	0.39	0.35	0.001	99.7	0.33	0.29	0.001	99.6
Lead	0.003	0.003	<0.001	>66.7	0.003	0.003	<0.001	>66.7
Magnesium								
Manganese	0.095	0.13	0.009	93.0	0.098	0.16	0.01	93.7
Mercury								
Nickel								
Zinc	0.48	1.6	0.2	87.5	0.42	0.77	0.045	94.1

* All concentrations are in mg/L except colour, turbidity and pH.

Cont'd.../

TABLE A-1 (Cont'd). RESULTS FOR PILOT PLANT OPERATION USING ONLY 5 $NaCl_{90}$ MODULES (PART 2)

	←75% Recovery				2413 kPa →			
Date Time	Nov. 7/74 14:30 - 23:00				Nov. 8/74 23:00 - 8:00			
Sample No.	Feed* 121	Conc* 125	Perm* 122	% Rej.	Feed 123	Conc 126	Perm 124	% Rej.
pH								
TOC	7.5	12.5	1	92.0	7.0	17.5	2	88.5
TIC	7.0	13.5	2	85.1	6.0	17	2	88.2
TH ($CaCO_3$)	228	485	35	92.7	227	651	45.7	92.9
TDS	600	1190	174	85.3	591	1550	208	86.5
DFS	474	962	130	86.4	468	1270	155	87.8
SS	8.4	8.4	<1	>88.1	8.4	10.8	1	90.7
Colour (CU)	5	10	<5	>50.0	5	20	<5	>75.0
Turb. (JTU)	2.6	2.3	0.3	86.9	2.2	3.2	0.2	93.7
Cl^-	165	325	41	87.3	173	450	52	88.4
$SO_4^=$								
COD	22.8	37.6	3.7	90.1	22.8	52.5	8.4	84.0
Aluminum	0.18	0.21	0.001	99.5	0.20	0.2	0.001	99.5
Cadmium	0.022	0.034	0.002	94.1	0.023	0.049	<0.003	>93.8
Chromium	0.018	0.025	0.001	96.0	0.013	0.018	0.001	94.4
Cobalt								
Copper	0.032	0.081	0.006	92.5	0.029	0.1	0.008	92.0
Iron	0.53	0.49	0.001	99.1	0.45	0.46	0.004	99.1
Lead	0.003	0.004	<0.001	>75.0	0.003	0.004	<0.001	>75.0
Magnesium								
Manganese	0.095	0.16	0.012	92.5	0.11	0.25	0.017	93.2
Mercury								
Nickel								
Zinc	0.40	0.58	0.033	94.3	0.44	0.76	0.042	94.4

* All concentrations are in mg/L except colour, turbidity and pH.

Cont'd.../

TABLE A-1 (Cont'd). RESULTS FOR PILOT PLANT OPERATION USING ONLY 5 $NaCl_{90}$ MODULES (PART 2)

	← 85% Recovery				2413 kPa →			
Date Time	Nov. 12/74 14:00 - 22:20				Nov. 13/74 22:30 - 7:30			
Sample No.	Feed* 127	Conc* 131	Perm* 128	% Rej.	Feed 129	Conc 132	Perm 130	% Rej.
pH								
TOC	10.0	22.5	1	95.5	9.5	30.5	1	96.7
TIC	14.0	27	2	92.5	14.5	32	2	93.7
TH ($CaCO_3$)	211	471	27.2	94.2	207	753	40.5	94.6
TDS	636	1300	162	87.5	636	2000	242	96.6
DFS	548	1090	123	88.7	562	1720	192	87.9
SS	7.6	13.6	1	92.6	5.6	14.4	<1	>93.0
Colour (CU)	10	30	5	83.3	10	50	<5	90.0
Turb. (JTU)	2.8	5.3	0.1	98.1	2.2	5	0.1	98.0
Cl^-	132	290	37	87.2	120	450	57	87.3
$SO_4^=$								
COD	22.8	53.2	2.8	94.7	25.6	72	2.4	96.6
Aluminum	0.24	0.34	0.001	99.7	0.20	0.35	0.001	99.7
Cadmium	0.013	0.016	0.001	93.7	0.012	0.022	0.001	95.4
Chromium	0.018	0.16	0.004	97.5	0.016	0.021	0.001	95.2
Cobalt								
Copper	0.046	0.14	0.004	97.1	0.046	0.2	0.008	96.0
Iron	0.60	1.1	0.002	99.8	0.45	0.76	0.001	99.8
Lead	0.004	0.01	0.001	90.0	0.004	0.007	0.001	85.7
Magnesium								
Manganese	0.077	0.14	0.006	95.7	0.039	0.15	0.007	95.3
Mercury								
Nickel								
Zinc	0.21	0.23	0.005	97.8	0.18	0.27	0.007	97.4

* All concentrations are in mg/L except colour, turbidity and pH.

Cont'd.../

TABLE A-1 (Cont'd). RESULTS FOR PILOT PLANT OPERATION USING ONLY 5 $NaCl_{90}$ MODULES (PART 2)

	←75% Recovery				2413 kPa→			
Date Time	Nov. 13/74 14:00 - 22:30				Nov. 14/74 22:30 - 7:30			
Sample No.	Feed* 133	Conc* **	Perm* 134	% Rej.	Feed 135	Conc **	Perm 136	% Rej.
pH								
TOC	8.5		0.5	94.1	7.5		0.5	93.3
TIC	15		2.5	83.3	15		2.5	83.3
TH ($CaCO_3$)	213		23.2	89.1	211		121	42.7
TDS	655		149	77.2	643		205	68.1
DFS	543		116	78.6	526		167	68.3
SS	4.4		<1	>77.2	6.8		<1	>85.3
Colour (CU)	20		<5	>75.0	10		<5	>50.0
Turb. (JTU)	2.7		0.2	92.5	3.5		1.2	65.7
Cl^-	140		33	76.4	135		33	75.6
$SO_4^=$								
COD	28.1		6.9	75.4	28.6		2.7	90.6
Aluminum	0.19		0.031	83.6	0.2		0.095	52.5
Cadmium	0.011		0.001	90.9	0.011		<0.001	>90.9
Chromium	0.025		0.001	90.9	0.033		<0.001	>97.0
Cobalt								
Copper	0.039		0.003	92.3	0.038		0.003	92.1
Iron	0.47		0.035	92.5	0.48		0.013	97.3
Lead	0.003		<0.001	>66.7	0.003		0.003	0
Magnesium								
Manganese	0.31		0.002	93.5	0.03		<0.001	>96.7
Mercury								
Nickel								
Zinc	0.18		0.005	97.2	0.18		0.015	91.7

* All concentrations are in mg/L except colour, turbidity and pH.
**Water sampler malfunction.

Cont'd.../

TABLE A-1 (Cont'd). RESULTS FOR PILOT PLANT OPERATION USING ONLY 5 $NaCl_{90}$ MODULES (PART 2)

	←85% Recovery				2413 kPa→			
Date Time	Nov. 14/74 13:45 - 22:15				Nov. 15/74 22:15 - 7:15			
Sample No.	Feed* 137	Conc* 141	Perm* 138	% Rej.	Feed 139	Conc 142	Perm 140	% Rej.
pH								
TOC	2.5	12.5	0.5	96.0	3.5	25	0.5	98.0
TIC	12.5	20.5	2.5	87.8	11.5	26	2.5	90.4
TH ($CaCO_3$)	212	474	36.4	92.3		786	43.9	94.4
TDS	639	1280	154	88.0	637	2100	245	88.3
DFS	548	1090	121	88.9	547	1770	196	88.9
SS	10	8.4	<1	>88.1	13.6	14.8	<1	>93.2
Colour (CU)	10	30	<5	>83.3	10	50	<5	>90
Turb. (JTU)	3.2	3	0.2	93.3	4.6	5.2	0.1	98.1
Cl^-	136	292	39	86.6	144	464	67	85.6
$SO_4^=$								
COD	25.4	41.3	2.7	93.5	29.7	70.5	3.2	95.5
Aluminum	0.27	0.22	0.002	99.1	0.26	0.31	0.001	99.7
Cadmium	0.011	0.016	<0.001	>93.8	0.012	0.03	0.001	96.7
Chromium	0.17	0.25	0.005	98.0	0.56	0.34	0.008	97.6
Cobalt								
Copper	0.039	0.084	0.003	96.4	0.041	0.14	0.004	97.1
Iron	0.59	0.47	0.001	99.8	0.79	0.7	0.001	99.9
Lead	0.005	0.004	<0.001	>75	0.005	0.006	<0.001	>83.3
Magnesium								
Manganese	0.025	0.038	0.004	89.5	0.032	0.067	0.003	95.5
Mercury								
Nickel								
Zinc	0.18	0.2	0.008	96	0.20	0.33	0.011	96.7

* All concentrations are in mg/L except colour, turbidity and pH.

Cont'd.../

APPENDIX B

Summary of Results for Spiked Heavy Metals Studies

TABLE B-1. SUMMARY OF RESULTS FOR SPIKED HEAVY METALS STUDIES

←——Batch Spiked ≃5 mg/L 2413 kPa ——→

Date Time	Dec. 4/74 13:15 - 20:45			Dec. 4 & 5/74 20:45 - 4:45			Dec. 5/74 4:45 - 12:45		
Sample No.	Feed * 143	Perm * 144	% Rej.	Feed 145	Perm 146	% Rej.	Feed 147	Perm 148	% Rej.
pH									
TOC	6.5	1.5	76.9	5.5	1.5	72.7	6.0	1.5	75.0
TIC	2.0	0.5	75.0	0.5	0.5	0	0.5	0.5	0
TH ($CaCO_3$)									
TDS	755	118	84.4	763	123	83.9	774	126	83.7
DFS	621	86.8	86.0	625	88.4	85.9	633	92.4	85.4
SS	34.4	1	97.1	17.2	1	94.2	18.1	1	94.5
Colour (CU)	5	5	0	5	5	0	5	5	0
Turb. (JTU)	17	0.4	97.7	9	0.4	95.6	10	0.4	96.0
Cl^-	221	36	83.7	229	38	83.4	233	39	83.3
$SO_4^=$									
COD	31.7	4	87.4	22.8	2.5	89.0	23.8	4	83.2
Aluminum	2.2	0.001	≃100	1.2	0.003	99.8	1.2	0.03	99.8
Cadmium	3.5	0.28	92.0	3.7	0.38	89.7	4.0	0.38	90.5
Chromium	2.2	0.005	99.8	1.0	0.004	99.6	1.2	0.003	99.8
Cobalt	4.2	0.39	90.7	4.2	0.5	88.1	4.4	0.52	88.2
Copper	2.1	0.008	99.6	1.2	0.019	98.4	1.4	0.027	98.1
Iron	2.3	0.013	99.4	1.1	0.003	99.7	1.3	0.001	99.9
Lead	2	0.001	≃100	0.83	0.001	99.9	0.96	0.003	99.7
Magnesium	19	1.9	90.0	19	2.2	88.4	19	2.2	88.4
Manganese	4	0.41	89.8	4.2	0.48	88.6	4.4	0.48	89.1
Mercury	2.6			2.6			2.1		
Nickel	4	0.36	91.0	22.8	2.5	89.0	4.3	0.44	89.8
Zinc	3	0.22	92.7	3.2	0.32	90.0	3.5	0.34	90.3

* All concentrations are in mg/L except colour, turbidity and pH.

Cont'd.../

TABLE B-1 (Cont'd). SUMMARY OF RESULTS FOR SPIKED HEAVY METALS STUDIES

	←——Batch Spiked			2413 kPa ——→ 1 mg/L		
Date Time	Dec. 9/74 12:15 - 20:45			Dec. 9 & 10/74 20:45 - 5:45		
Sample No.	Feed * 149	Perm * 150	% Rej.	Feed 151	Perm 152	% Rej.
pH						
TOC	5	1.5	70.0	5	1.5	70.0
TIC	1	0.5	50.0	0.5	0.5	0
TH ($CaCO_3$)						
TDS	587	105	82.1	592	196	82.1
DFS	462	79.6	82.8	462	84.4	81.7
SS	16	1	93.8	8.4	1	88.1
Colour (CU)	5	5	0	5	5	0
Turb. (JTU)	6.7	0.3	95.5	4.4	0.3	93.2
Cl^-	187	31	83.4	189	32	83.1
$SO_4^=$						
COD	2.4	4		18.8	2	89.4
Aluminum	0.7	0.003	99.6	0.3	0.003	99.0
Cadmium	0.92	0.12	87.0	0.91	0.13	85.7
Chromium	0.58	0.005	99.1	0.25	0.003	98.8
Cobalt	0.86	0.11	87.2	0.89	0.12	86.5
Copper	0.85	0.027	96.8	0.62	0.043	93.1
Iron	0.75	0.001	99.9	0.39	0.001	99.7
Lead	0.48	0.004	99.2	0.21	0.004	98.1
Magnesium	15	2.1	86.0	15	2.1	86.0
Manganese	0.96	0.12	87.5	0.96	0.12	87.5
Mercury	1.8			1.6		
Nickel	0.92	0.12	87.0	0.9	0.12	86.7
Zinc	1.1	0.1	90.9	1.0	0.11	89.0

* All concentrations are in mg/L except colour, turbidity and pH.

Cont'd.../

TABLE B-1 (Cont'd). SUMMARY OF RESULTS FOR SPIKED HEAVY METALS STUDIES

← Batch Spiked 10 mg/L — 2413 kPa →

Date Time	Dec. 10/74 12:00 - 19:30			Dec. 10 & 11/74 19:30 - 3:30			Dec. 11/74 3:30 - 11:30		
Sample No.	Feed* 153	Perm* 154	% Rej.	Feed 155	Perm 156	% Rej.	Feed 157	Perm 158	% Rej.
pH									
TOC	6.5	1	84.6	8.5	2	76.5	6.5	1.5	76.9
TIC	0.5	0.5	0	0.5	0.5	0	0.5	0.5	0
TH ($CaCO_3$)									
TDS	830	160	80.7	825	174	78.9	799	180	77.5
DFS	658	126	80.9	673	136	79.8	648	141	78.2
SS	60	1	98.3	58.8	1	98.3	54.8	1	98.2
Colour (CU)	5	5	0	5	5	0	5	5	0
Turb. (JTU)	35	0.3	99.1	34	0.3	99.1	32	0.4	98.8
Cl^-	272	58	78.7	275	64	76.7	268	65	75.7
$SO_4^=$									
COD	27.7	15.3	44.8	28.2	16.3	42.2	34.7	14.4	58.5
Aluminum	5.4	0.07	98.7	4.9	0.006	99.9	4.4	0.015	99.7
Cadmium	8.8	1.4	84.1	9	1.6	82.2	9.2	1.6	82.6
Chromium	5.3	0.023	99.6	5.1	0.012	99.8	4.2	0.008	99.8
Cobalt	8.6	1.4	83.7	8.8	1.6	81.8	9.1	1.6	82.4
Copper	5.8	0.3	94.8	5.8	0.44	92.4	5.8	0.49	91.6
Iron	5.5	0.078	98.6	5	0.001	≃100	4.5	0.003	99.9
Lead	4.2	0.008	99.8	3.4	0.015	99.6	3.1	0.019	99.4
Magnesium	25	4.1	83.6	25	4.4	82.4	25	4.5	82
Manganese	8.8	1.4	82.7	8.9	1.6	82.0	9.2	1.7	81.5
Mercury	1.1								
Nickel	8.1	1.4	82.7	8.5	1.5	82.4	8.5	1.6	81.2
Zinc	8.3	1.3	84.3	8.5	1.5	82.4	8.8	1.6	81.8

* All concentrations are in mg/L except colour, turbidity and pH.

Cont'd.../

TABLE B-1 (Cont'd). SUMMARY OF RESULTS FOR SPIKED HEAVY METALS STUDIES

	←Batch Spiked 1 mg/L			2413 kPa→		
Date Time	Dec. 11/74 15:15 - 22:45			Dec. 12/74 22:45 - 6:45		
Sample No.	Feed* 159	Perm* 160	% Rej.	Feed 161	Perm 162	% Rej.
pH						
TOC	6.5	1.5	76.9	6	1.5	75.0
TIC	0.5	0.5	0	0.5	0.5	0
TH ($CaCO_3$)						
TDS	689	144	79.1	317	136	57.1
DFS	603	117	80.6	226	108	52.2
SS	20	1	95.0	13.6	1	92.6
Colour (CU)	5	5	0	10	5	50.0
Turb. (JTU)	8.9	4	95.5	6.3	0.2	96.8
Cl^-	218	45	79.4	233	46	80.3
$SO_4^=$						
COD	27.2	1.4	94.9	33.7	1.4	95.9
Aluminum	0.87	0.015	98.3	0.6	0.018	97.0
Cadmium	1.2	0.21	82.5	1.2	0.19	84.2
Chromium	0.8	0.005	99.4	0.65	0.003	99.5
Cobalt	0.98	0.17	82.7	0.97	0.12	87.6
Copper	1.3	0.09	93.1	1.2	0.12	90.0
Iron	1.1	0.005	99.6	0.72	0.013	98.2
Lead	0.86	0.009	99.0	0.6	0.007	98.8
Magnesium	16	2.7	83.1	17	2.7	84.1
Manganese	1.1	0.17	84.6	1.1	0.17	84.6
Mercury	2.6			4.1		
Nickel	1	0.17	83.0	0.92	0.22	76.1
Zinc	1.3	0.2	84.6	1.3	0.2	84.6

* All concentrations are in mg/L except colour, turbidity and pH.

Cont'd.../

TABLE B-1 (Cont'd). SUMMARY OF RESULTS FOR SPIKED HEAVY METALS STUDIES

	←Batch Spiked 5 mg/L 2413 kPa→					
Date Time	Dec. 13/74 11:30 - 19:00			Dec. 14/74 19:00 - 3:00		
Sample No.	Feed* 163	Perm* 164	% Rej.	Feed 165	Perm 166	% Rej.
pH						
TOC	7	1.5	78.6	7.5	1.5	80.0
TIC	0.5	0.5	0	0.5	0.5	0
TH ($CaCO_3$)						
TDS	756	179	76.3	802	194	75.8
DFS	650	144	77.9	687	157	77.2
SS	444	1	97.8	38	1	97.4
Colour (CU)	5	5	0	5	5	0
Turb. (JTU)	28	0.2	99.3	22	0.3	98.6
Cl^-	234	51	78.2	253	56	77.9
$SO_4^=$						
COD	33.2	3	91.0	30.2	4.5	85.1
Aluminum	3	0.013	99.6	2.3	0.032	98.6
Cadmium	4.8	0.74	84.6	5	0.8	84.0
Chromium	2.8	0.012	99.6	2.2	0.01	99.6
Cobalt	4.5	0.77	82.9	4.7	0.8	83.0
Copper	3.3	0.18	94.5	3.3	2.6	92.1
Iron	3.1	0.008	99.7	2.6	0.015	99.4
Lead	2.7	0.01	99.6	2.3	0.011	99.5
Magnesium	20	3.6	82.0	21	3.6	82.9
Manganese	4.6	0.78	83.0	4.7	0.82	82.6
Mercury	2.1			0.5		
Nickel	4.4	0.8	81.8	4.4	0.8	81.8
Zinc	4	0.64	84.0	4.4	0.78	82.3

* All concentrations are in mg/L except colour, turbidity and pH.

Cont'd.../

TABLE B-1 (Cont'd). SUMMARY OF RESULTS FOR SPIKED HEAVY METALS STUDIES

	←Batch Spiked 10 mg/L			2413 kPa→		
Date Time	Dec. 16/74 11:45 - 19:15			Dec. 16 & 17/74 19:15 - 3:15		
Sample No.	Feed * 167	Perm * 168	% Rej.	Feed 169	Perm 170	% Rej.
pH						
TOC	6	1	83.3	5	1	80.0
TIC	0.5	0.5	0	0.5	0.5	0
TH ($CaCO_3$)						
TDS	777	157	79.8	793	258	67.5
DFS	630	131	79.2	647	204	68.5
SS	34	1	97.1	55	1	98.2
Colour (CU)	10	5	50.0	10	5	50.0
Turb. (JTU)	24	0.8	96.7	22	0.2	99.1
Cl^-	268	53	80.2	277	57	79.4
$SO_4^=$						
COD	21.8	2.5	88.5	20.3	4	80.3
Aluminum	5.9	0.002	≃100	4.1	0.004	99.9
Cadmium	8.8	1.5	83.0	9.2	1.8	80.4
Chromium	5.8	0.03	99.5	4.2	0.02	99.5
Cobalt						
Copper	6.1	0.37	93.9	5.6	0.67	88.0
Iron	5.8	0.001	≃100	4.3	0.001	100
Lead	4.9	0.013	99.7	3.3	0.037	98.9
Magnesium	26	43	83.5	26	5.2	80.0
Manganese	8.9	1.5	83.2	9.1	1.8	80.2
Mercury	9	1.5	83.3	9	1.8	80.0
Nickel	9.9	1.7	82.8	9.9	2.2	77.8
Zinc	8.5	1.3	84.7	8.5	1.8	78.8

* All concentrations are in mg/L except colour, turbidity and pH.

Cont'd.../

TABLE B-1 (Cont'd). SUMMARY OF RESULTS FOR SPIKED HEAVY METALS STUDIES

	←Batch Spiked 5 mg/L 2413 kPa→					
Date Time	Dec. 17/74 11:30 - 19:00			Dec. 17 & 18/74 19:00 - 3:00		
Sample No.	Feed * 171	Perm * 172	% Rej.	Feed 173	Perm 174	% Rej.
pH						
TOC	4.5	2	55.6	4	1	75.0
TIC	0.5	0.5	0	0.5	0.5	0
TH ($CaCO_3$)						
TDS	607	146	76.0	718	143	80.1
DFS	538	107	80.1	579	107	81.5
SS	35	1	97.1	32	1	96.9
Colour (CU)	10	5	50.0	20	5	75.0
Turb. (JTU)	15	0.1	97.1	13	0.3	97.7
Cl^-	223	42	81.2	237	44	81.4
$SO_4^=$						
COD	16.4	3.9	76.2	17.1	6.8	60.2
Aluminum	2.7	0.008	99.7	2.5	0.01	99.6
Cadmium	5.3	0.88	83.4	5.5	0.91	83.5
Chromium	2.6	0.013	99.5	2.4	0.008	99.7
Cobalt						
Copper	3.5	0.3	91.4	3.8	0.44	88.4
Iron	3.1	0.001	≃100	2.4	0.001	≃100
Lead	2.7	0.029	98.9	2.6	0.036	98.6
Magnesium	21	3.7	82.4	21	3.8	81.9
Manganese	5	0.9	82.0	5	0.94	81.2
Mercury	5	0.88	82.4	5	0.92	81.6
Nickel	5	0.84	83.2	5	0.88	82.4
Zinc	4.7	0.74	84.3	5	0.82	83.6

* All concentrations are in mg/L except colour, turbidity and pH.

Cont'd.../

TABLE B-1 (Cont'd). SUMMARY OF RESULTS FOR SPIKED HEAVY METALS STUDIES

	←Batch Spiked 10 mg/L			2413 kPa→					
Date Time	Dec. 18/74 12:45 - 20:15			Dec. 19/74 20:15 - 4:15			Dec. 19/74 4:15 - 12:15		
Sample No.	Feed * 175	Perm * 176	% Rej.	Feed 177	Perm 178	% Rej.	Feed 179	Perm 180	% Rej.
pH									
TOC	2	1	50.0	2.5	1	60.0	1.5	1	33.3
TIC	0.5	0.5	0	0.5	0.5	0	0.5	0.5	0
TH ($CaCO_3$)									
TDS	410	82.4	79.9	410	136	66.8	443	125	71.8
DFS	277	54	80.5	279	102	63.4	386	81.2	79.0
SS	73.6	1	98.6	59.2	1	98.3	40.4	1	97.5
Colour (CU)	5	5	0	5	5	0	5	5	0
Turb. (JTU)	19	0.1	99.5	20	0.1	99.5	16	0.1	99.4
Cl^-	207	40	80.7	196	44	77.6	203	49	75.9
$SO_4^=$									
COD	13.7	2.9	78.8	6.3	1.5	76.2	6.8	2.4	64.7
Aluminum	7.4	0.01	99.9	5.3	0.012	99.8	9.4	2.4	74.5
Cadmium	9.5	1.7	82.1	9.5	2.4	74.7	3.6	0.017	99.5
Chromium	7.3	0.036	99.5	5.5	0.014	99.8	3.7	0.01	99.7
Cobalt	9.3	1.8	80.7	9.3	2.2	76.3	9.4	2.5	73.4
Copper	8.3	0.82	90.1	7.8	0.98	87.4	6.9	1.2	32.6
Iron	7.1	0.001	≃100	5.3	0.001	≃100	4	0.002	100
Lead	6	0.19	96.8	4.7	0.43	90.9	3.8	0.43	88.7
Magnesium	18	3.8	78.9	18	4	77.8	18	5	72.2
Manganese	9.2	1.7	81.5	9.2	2.2	76.1	9.4	2.6	72.3
Mercury	4.5			2.6			2.1		
Nickel	8.6	1.7	80.2	8.6	1.9	77.9	8.8	2.4	72.7
Zinc	9.2	1.8	80.4	9.2	2	78.3	9.4	2.4	74.5

* All concentrations are in mg/L except colour , turbidity and pH.

Cont'd.../

TABLE B-1 (Cont'd). SUMMARY OF RESULTS FOR SPIKED HEAVY METALS STUDIES

	←Continuous Spiked 1 mg/L				2413 kPa→			
Date Time	Dec. 19/74 14:45 - 20:15				Dec. 20/74 20:15 - 2:15			
Sample No.	Feed* 181	Conc* 183	Perm* 182	% Rej.	Feed 187	Conc 189	Perm 188	% Rej.
pH								
TOC	8	9	0.5	94.4	9	10.5	0.5	95.2
TIC	19	3	1.5	50.0	19.9	1.5	2	-
TH ($CaCO_3$)								
TDS	577	432	286	33.8	614	550	352	36.0
DFS	474	347	211	39.2	470	438	270	38.4
SS	8.4	51	1	98.0	12	67	1	98.5
Colour (CU)	20	30	5	83.3	20	40	5	87.5
Turb. (JTU)	2.8	23	0.2	99.1	3.8	42	0.2	99.5
Cl^-	134	396	86	78.3	130	474	118	75.1
$SO_4^=$								
COD	234	386	0.3	99.2	26.8	44.4	0.3	99.3
Aluminum	0.45	3.7	0.019	99.5	0.32	5.5	0.009	99.8
Cadmium	0.14	4.7	0.87	81.5	0.11	6.9	1.4	79.7
Chromium	0.24	2.6	0.021	99.2	0.16	3.8	0.032	99.2
Cobalt	0.10	4.4	0.83	81.1	0.076	6.9	0.5	92.8
Copper	0.31	2.5	0.35	86.0	0.26	2.2	0.28	87.3
Iron	0.3	0.3	0.001	≃100	0.25	3.7	0.001	≃100
Lead	0.21	2.1	0.091	95.7	0.11	2.3	0.049	97.9
Magnesium	17	30	6.6	78.0	17	40	10	75.0
Manganese	0.12	4.3	0.88	79.5	0.1	6.8	1.5	77.9
Mercury	5	3.6			2.1	0.5		
Nickel	0.1	4.1	0.86	79.0	0.079	6.4	0.4	93.8
Zinc	0.21	4	0.71	82.3	0.24	5.6	0.1	98.2

* All concentrations are in mg/L except colour, turbidity and pH.

Cont'd.../

TABLE B-1 (Cont'd). SUMMARY OF RESULTS FOR SPIKED HEAVY METALS STUDIES

Date Time	Dec. 20/74 2:15 - 8:15				Dec. 20/74 8:15 - 14:15			
Sample No.	Feed* 187	Conc* 189	Perm* 188	% Rej.	Feed 191	Conc 190	Perm 192	% Rej.
pH								
TOC	11.5	15.5	1.5	90.3	12	20	1.5	92.5
TIC	25	3	1.5	50.0	19	3	1	66.7
TH ($CaCO_3$)								
TDS	645	611	428	30.0	660	613	477	22.2
DFS	497	479	330	31.1	485	475	340	28.4
SS	15.2	100	1	99.0	18.8	119	1	99.2
Colour (CU)	20	40	5	87.5	20	40	5	87.5
Turb. (JTU)	5.7	59	0.3	99.5	5.7	68	0.3	99.6
Cl^-	144	520	140	73.1	154	532	140	73.7
$SO_4^=$								
COD	29.8	55.1	8.8	84.0	337	63.9	9.3	85.5
Aluminum	0.35	9.2	0.012	99.9	0.3	10.9	0.017	99.8
Cadmium	0.07	8	1.9	76.3	0.05	8.4	2.4	71.4
Chromium	0.13	5.1	0.034	99.3	0.13	5.8	0.032	99.4
Cobalt	0.02	100	1.8	98.2	0.006	8.3	2.2	73.5
Copper	0.19	1.7	0.31	81.8	0.17	1.3	0.38	70.8
Iron	0.38	5	0.005	99.9	0.4	5.5	0.018	99.7
Lead	0.11	3.1	0.04	98.7	0.1	3.4	0.044	98.7
Magnesium	16	42	10	76.2	19	42	13	69.1
Manganese	0.018	7.6	1.8	76.3	0.012	8	2.2	72.5
Mercury	1.1	1.1			1.1	1.1		
Nickel	0.024	7.2	1.7	76.4	0.012	7.4	2	73.0
Zinc	0.2	7.3	1.6	78.1	0.22	7.8	1.9	75.6

* All concentrations are in mg/L except colour, turbidity and pH.

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